RADIATION RESEARCH **166**, 219–254 (2006)
0033-7587/06 $15.00

Dose Estimation for Atomic Bomb Survivor Studies: Its Evolution and Present Status

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Cullings, H. M., Fujita, S., Funamoto, S., Grant, E. J., Kerr, G. D. and Preston, D. L. Dose Estimation for Atomic Bomb Survivor Studies: Its Evolution and Present Status. ***Radiat. Res.*** **166, 219–254 (2006).**

In the decade after the bombings of Hiroshima and Nagasaki, several large cohorts of survivors were organized for studies of radiation health effects. The U.S. Atomic Bomb Casualty Commission (ABCC) and its U.S./Japan successor, the Radiation Effects Research Foundation (RERF), have performed continuous studies since then, with extensive efforts to collect data on survivor locations and shielding and to create systems to estimate individual doses from the bombs' neutrons and γ rays. Several successive systems have been developed by extramural working groups and collaboratively implemented by ABCC and RERF investigators. We describe the cohorts and the history and evolution of dose estimation from early efforts through the newest system, DS02, emphasizing the technical development and use of DS02. We describe procedures and data developed at RERF to implement successive systems, including revised rosters of survivors, development of methods to calculate doses for some classes of persons not fitting criteria of the basic systems, and methods to correct for bias arising from errors in calculated doses. We summarize calculated doses and illustrate their change and elaboration through the various systems for a hypothetical example case in each city. We conclude with a description of current efforts and plans for further improvements.

INTRODUCTION

Studies of large cohorts of Hiroshima and Nagasaki atomic bomb survivors and their children being carried out by scientists at the Radiation Effects Research Foundation (RERF) are of central importance to radiation epidemiology and risk assessment. The availability of reliable, well-characterized, individual dose estimates for members of these cohorts is a *sine qua non* in describing radiation effects on the health of the survivors and their children and in generalizing these risk estimates for wider use in the radiation protection of workers and the general public. The atomic bomb survivors considered as a cohort are unique among exposed groups studied in radiation epidemiology. Demographically, the group is large and diverse, consisting of the entire populations of two cities, including several hundred thousand individuals of all ages and both sexes. Persons in the group were exposed to the direct radiation from the bombs due to their presence in the cities at the time of the bombings and not for particular medical or occupational reasons. The radiation doses were truly acute, being received almost completely in a matter of seconds; furthermore, every person in each city received the dose at the same time, and the bombings in the two cities were only 3 days apart.

From a physical standpoint, the doses came from penetrating external radiations arising from a large, localized source, so that a systematic calculation is possible. Of course there were no radiation measuring devices present at the bombings in Japan, but special methods have been devised to use materials that were present at the time to make retrospective measurements of the radiation doses or fluences that were received in relatively unshielded locations. In addition, measurements of tested nuclear weapons and simulations using other sources have provided useful information.

Because persons were present at all distances, as measured from the point directly below the bomb (the hypocenter), and because many of those who survived were shielded from the full radiation intensity at their particular distance, by being in or near buildings or terrain, the doses received by survivors range from lethal (i.e., doses in excess of the estimated human LD_{50} or some other measure of population average lethal dose) to infinitesimal. Although the information on shielding and location is imperfect and varies among individuals, considerable detailed information is available for a large proportion of survivors within about 2 km of the hypocenters. Somewhat less detailed information is available for another substantial portion of such proximal survivors and for a large portion of more distal survivors, as described below. Methods have also been devised to perform biodosimetric measurements

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that provide some limited information on doses in certain subsets of survivors.

Other cohorts share some of these features, but none share all of them. Correspondingly, extensive efforts have been devoted to the dosimetry. Scientists in Japan and the U.S. have worked over a period of almost 60 years to create the best feasible dosimetry system for estimating the doses of individual survivors and to validate its performance. This has resulted in several generations of survivor dosimetry systems, which are discussed here.

RERF's current epidemiological studies are rooted in the organizational efforts and early studies carried out between 1947 and 1975 by the researchers of its predecessor, the Atomic Bomb Casualty Commission (ABCC). Because there were no credible dose estimates, the early ABCC studies and the original definitions of the current study cohorts used distance from the hypocenter as a surrogate for exposure and dose. The earliest survivor dosimetry system, called T57D, became available in the late 1950s and consisted of simple plots of (total) γ-ray and neutron ''air dose'' as a function of distance, with a basic adjustment for shielding. Over the ensuing decades, succeeding systems have become much more sophisticated. The current system (called DS02) provides detailed information on the fluences of neutrons and γ rays from various sources associated with the fissioning material in the bombs and the debris in the ensuing fireballs, as described in more detail below, as a function of energy and direction, received at specific shielded locations or in specific organs of individual survivors with sufficient shielding information. These fluence data are summed with appropriate weights to convert them into the shielded kerma and organ dose estimates used as the basis of risk estimation.

The evolution of the survivor dosimetry has been driven in large measure by the prodigious increases in computer speed over the last few decades and the concomitant development of computationally intensive numerical methods. This has facilitated a shift from methods based on empirical description of results of experiments conducted during nuclear weapons tests and other experiments in Nevada, which could not completely simulate the exposure conditions in Hiroshima and Nagasaki, to calculations based on detailed information on the nature of the bombs and the basic principles of physical interactions of individual particles and quanta of radiation. The development of the dosimetry systems has also benefited from newer physical data and newer ideas about how to assess the effect of shielding. As a result, the current computational models incorporate much more detailed information about the actual physical environment of the bombs. The credibility of DS02 has been bolstered by extensive new comparisons of calculated results with thermoluminescence and neutron activation measurements in materials exposed to radiation from the Hiroshima and Nagasaki bombs.

All of the basic dosimetry systems that have been used at ABCC and RERF were developed and approved by outside physicists and weapons experts. The core systems that have been provided to RERF can be used directly to compute doses for only about 55% of the survivors of interest to our studies. Thus the implementation of a complete dosimetry requires carefully constructed extensions to the core system to account for estimates of dose to the remaining 45%. In addition, from our understanding of how the rather large random errors in individual dose estimates can affect risk estimates, we have come to recognize that relatively simple steps could be taken to reduce bias arising from these errors. Separately derived error adjustments based on statistical theory are an explicit part of RERF's implementation of the current dosimetry.

In this paper, we first present a description of the population of people whose exposure status and dose are of interest in risk estimation and give a brief discussion of the nature and sources of data on location and shielding for individual survivors. After an introduction to basic concepts and definitions, we briefly describe the earlier dosimetry systems (T57D, T65D and DS86) and why improvements were needed in each. This is followed with a more detailed description of the development of the current dosimetry system (DS02). We then describe RERF's implementation and extension of the dosimetry system (including dose error adjustments). We conclude with a short description of how we believe that the dose estimates may be improved in coming years.

POPULATIONS OF INTEREST

The RERF Exposure Status and Dose Master Roster

RERF research is primarily focused on the characterization of radiation effects in three groups of people:

1. People with potential direct, postnatal exposure to radiation from the atomic bombs (generally called ''survivors'' even though some of these people had no radiation exposure).
2. People who were or could have been exposed *in utero.*
3. People conceived after the bombings whose parents were or could have been exposed to radiation from the bombs (called the second or ''F1'' generation).

To carry out the studies and provide useful quantitative estimates of radiation risks, it is essential to have well-characterized descriptions of exposure status and dose for the survivors, for mothers of those exposed *in utero,* and for the parents of people considered in the F1 studies.

RERF research is currently focused on three cohorts:

1. The Life Span Study (LSS) atomic bomb survivor cohort, which includes 93,741 people who were within 10 km of the hypocenter in either Hiroshima or Nagasaki at the time of the bombings and 26,580 people who were not in the cities at the time of the bombings. LSS cohort members are all known to have survived until at least

TABLE 1
Summary Information on RERF Dosimetry Roster

Exposure status	Study group: LSS	In-utero mothers	F1 mortality parents	Other[a]	T65D/DS86 roster[a]	Current roster[a]
Exposed <3 km	68,179	1,500	27,066	3,976	78,347	82,656
Exposed 3–10 km	25,562	854	19,450	15,733	35,241	52,970
Exposed, location unknown			21	222	6	240
Unexposed (i.e. >10 km)	26,580	630	42,714	43,345	26,580	106,740
Exposure status unknown		647	10,153	145		11,025
Total	120,321	3,631	99,404	63,421	140,174	253,617

[a] The column ''Other'' includes parents of children in early genetic studies and persons with information on acute effects who are not in any of the groups in the first three columns. Numbers in the ''Current roster'' column are not sums of the numbers in the corresponding rows of the ''Study group'' columns, because there is considerable overlap among the study groups listed in the first three columns.

October 1, 1950. See, for example, refs. (*1, 2*) for more information.

2. The in-utero cohort, which includes 3,638 people born in Hiroshima and Nagasaki between the date of the bombings and mid May 1946. The best description of the current in-utero cohort is given in ref. (*3*).
3. The F1 mortality cohort, which consists of 76,814 people born in Hiroshima or Nagasaki between May 1946 and the end of 1984, and its extensions, which include an additional 11,667 people born in the cities during this period who were selected for, and in many cases participated in, clinical and laboratory studies carried out at ABCC and RERF during the 1970s and 1980s. The F1 mortality cohort has recently been described in ref. (*4*), while information about the other studies, primarily aimed at genetic end points, is given in refs. (*5–7*).

The remainder of the current roster includes some persons not in these three major groups, such as some parents of children in early genetic studies and some persons with information on acute effects, as shown in Table 1 (''Other'').

RERF also carries out special clinical studies that involve subsets of the LSS, in-utero and F1 mortality cohorts. A group of particular interest in this regard is the Adult Health Study (AHS) sub-cohort, a subset of the LSS and in-utero cohorts that was selected to include a large number of survivors with high doses. AHS members participate in biannual clinical examinations at RERF(*8*).

Since all of these cohorts originated in the 1950s when reliable dose estimates were not available, they were initially defined in terms of groups based on distance from the hypocenter, as recommended by the Francis committee in 1955 (*9*). The first group, usually called the ''inner proximal'' group, involved persons who were at distances less than 2 km at the time of the bombings. This distance had first been recognized as one beyond which clinical signs of acute radiation exposure had not been observed at significant levels [see, e.g., Table 7.1 of ref. (*10*); (*11*)]. An early unpublished ABCC study reported by Woodbury in 1954 had compared early mortality in the interval 1950–1954 in survivors within 2 km to those between 2 and 4 km and found indications of increased mortality in the former compared to the latter (*12*). By the time that the major study groups were defined in the late 1950s (*1*, *12*), the dose with no shielding at 2 km was estimated by T57D to be about 15 rad ''air dose'' (150 mGy) in both cities (*13*). The group between 2 km and 2.5 km was called ''outer proximal'', 2.5 km being a distance within which doses were felt to be ''appreciable''; unshielded doses at 2.5 km were estimated by T57D to be about 3 rad air dose (30 mGy) (*13*). Because of their limited numbers and their ''appreciable'' exposure, all persons within 2.5 km who met the study criteria were included in these groups (*1, 12*).

The Francis committee had also recommended two comparison groups without appreciable exposure that would be of similar size to the ''inner proximal'' group: a group of persons at more distal locations >2.5 km in the cities at the time of the bombings, and an ''unexposed'' group who were not in the cities at the time of the bombings but had returned there by about 1950 when relevant census data were collected. The latter, ''not in city'' group was defined separately and was added to ''guard against the risk of missing effects that are not dose-dependent and against error in assigning radiation dose to those in the city but far from the hypocenter when the bomb fell'' (*13*). ''Not in city'' was taken to mean at least 10 km from the hypocenter at the time of the bombings; most of this group had returned to Hiroshima or Nagasaki after the bombings from more distant locations in Japan. Although a few of the persons in the ''distal'' group were actually located in the cities at distances beyond 10 km at the time of the bombings, they were classified together with the ''not in city'' group as ''unexposed''; hence the 10-km distance effectively distinguishes the ''distal exposed'' group from the ''unexposed'' group (*1*). In addition, to allow some consideration of potential exposure to residual radiation, persons in the ''unexposed'' group were classified as ''early entrants'' if they had entered the city, i.e. inside 10 km, within 30 days of the bombing, and as ''late entrants'' otherwise (*12*).

While some attention was paid to the in-utero and F1 groups, formal programs for dose estimation were focused primarily on the LSS cohort. As a result of these efforts, the documented T65D dosimetry roster contained 140,174 people, including all 93,741 exposed members of the LSS cohort, 19,853 exposed in-utero mothers and parents of members of the F1 mortality cohort members, and the 26,580 unexposed members of the LSS cohort. However, even at the time of the implementation of DS86 in the late 1980s, there was no comprehensive roster of people whose exposure status and dose estimates were relevant to RERF studies. Therefore, efforts to compute DS86 dose estimates were limited to people in the documented T65D roster from the major samples. This situation led to the exclusion of a number of exposed non-LSS F1 parents and in-utero members and prompted the development of various *ad hoc* and poorly documented methods of dose imputation for some survivors.

To avoid the problems that arose when DS86 was implemented, we have developed a new, comprehensive roster of survivors whose exposure status and dose are relevant to RERF studies: the *RERF Dosimetry and Exposure Status Roster*. This roster includes information on 253,617 people including 135,852 survivors, 106,740 people who were not in the cities at the time of the bombings, and 11,025 people whose exposure status is unknown. Table 1 summarizes information on the number of people in the current roster relevant to each of the major study groups by exposure status. The next to last column of the table indicates the number of people with documented DS86 (and T65D) dose estimates. The distinction between persons at distances <3 km and those at distances >3 km shown in the table has been used in recent years because it corresponded roughly to the distance at which DS86 free-in-air kerma, and hence maximum possible doses, were equal to 5 mGy. This was used as a cutoff value in the implementation of DS86, below which calculated doses were considered negligible and were set to zero. As discussed above, this cutoff was reduced to 0.5 mGy in the implementation of DS02.

Exposure Status and Shielding History Data Sources

The computation of individual survivor dose estimates requires information on location and, for exposed survivors, shielding at the time of the bombings. These data came from several sources: detailed shielding histories obtained for proximal survivors [i.e., the ‘‘most heavily exposed’’ (*12*) survivors, within 2 km of the hypocenters], Master File cards created during the 1950s and 1960s for each person of interest to RERF, the Master Sample Questionnaire administered to members of the major samples, and information from various early surveys (most notably the study of untoward pregnancy outcomes carried out between 1948 and 1954).

The Master File cards and the Master Sample Questionnaire contain information on location at the time of the bombings and limited information on the type of shielding that allows one to distinguish among people exposed in houses or other wooden structures, people who were in the open with little or no reported shielding, and some other groups. Location from these sources is generally coded with reference to wartime-era U.S. Army maps (*14, 15*) using grid points spaced 100 yards apart. More information on Master File cards and the Master Sample Questionnaire can be found in ABCC Technical Report 4-59 (*12*).

Information on the presence or absence of acute effects, including epilation, flash burns, bleeding and oropharyngeal lesions, is available for most proximal survivors and early entrants. These data were explicitly used as an exposure surrogate in the definition of the heavily exposed groups for some cohorts (most notably the AHS). In DS86 and DS02, as discussed below, they are used to a limited extent in decisions about shielding for proximal survivors with no reported external shielding.

Shielding histories, which provide the most comprehensive information on exposure conditions, were obtained from interviews of people who were close to the hypocenters, beginning in 1951 in Nagasaki and 1954 in Hiroshima (*16*). The format used in obtaining these histories was developed in conjunction with researchers at Oak Ridge National Laboratory who were involved with dose reconstruction (*17*). The strategies used in the two cities for compiling shielding histories were somewhat different because there were more survivors at ground distances less than 2,000 m at Hiroshima than at Nagasaki. At Nagasaki, shielding histories were compiled on most survivors who were located at ground distances less than 2,000 m. However, the approach at Hiroshima was to take shielding histories out to 2,000 m for only those survivors included in the smaller study sample (e.g., the AHS and in-utero samples). It was decided initially that shielding histories would only be taken on LSS participants who were located at ground distance of less than 1,200 m. After shielding histories were compiled on all LSS participants under 1,200 m, however, complete collection of shielding histories was extended to those under 1,300 m, and so forth. When the shielding interview program was terminated in 1965, histories had been obtained from most LSS survivors exposed within 1.6 km in Hiroshima and 2 km in Nagasaki.

Shielding histories contain detailed information on location, orientation, position and surroundings at the time of the bombings. Most histories contain (or refer to) a set of scaled drawings that provide a map of the neighborhood showing nearby structures together with plan and elevation views of the building in which the survivor was located (Fig. 1). The neighborhood drawings were probably based on the street plans of the U.S. Army maps in most cases, and smaller streets, houses, etc. were added based on other sources, including interviews and inspection of high-resolution aerial photos taken shortly before or after the bombings. For people who were exposed in houses or other light wooden structures, the building drawings were later used to code the information needed for the ‘‘nine-parameter’’

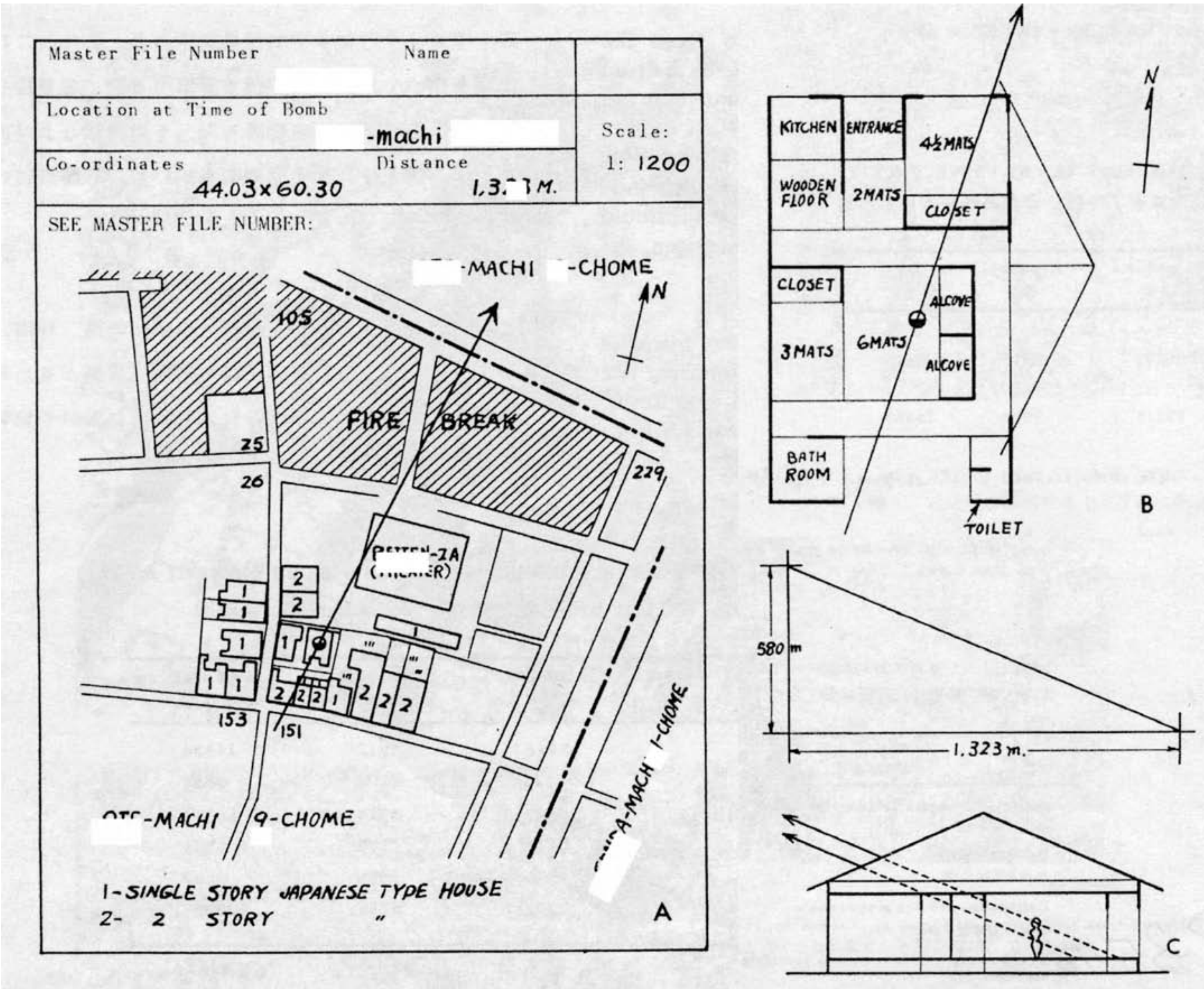

FIG. 1. Building and neighborhood drawings for a survivor.

formula used to compute T65D transmission factors or choose representative shielding cases for DS86 and DS02 computations (see below). For people with shielding histories, location was typically recorded with a 10-yard resolution on the U.S. Army maps.

For the populations of primary interest, Table 2 provides information on the number of survivors in the dose roster with known locations and the percentage of those who have shielding histories, by city and distance category.

BASIC CONCEPTS AND DEFINITIONS IN ATOMIC BOMB DOSIMETRY

All of the dosimetry systems provide estimates only for direct exposure to the radiations emitted by the bombs within a few minutes of their detonations, at locations within a few kilometers of the hypocenter. Thus the atomic bomb dosimetry systems consider only the doses from two external, penetrating types of ionizing radiation: neutrons and γ rays. Like other methods of dosimetry used in radiation epidemiology, atomic bomb survivor dosimetry starts from the fundamental assumption that a suitable measure of radiation for estimating quantitative relationships to health effects is the *absorbed dose* in relevant tissues, defined as the amount of energy *deposited* in the tissue from interactions of a specific type of ionizing radiation (neutrons or γ rays), per unit mass of tissue. Discussions of survivor dosimetry also mention tissue *kerma.* Tissue kerma (kinetic energy released in material) is defined as the energy per unit mass *released* by interactions of the neutrons or γ rays in a unit volume of tissue. The same units of grays (1 Gy = 1 J/kg) are used for both kerma and dose, consistent with definitions in ICRU Report 60 (*18*).

The distinction between dose and kerma arises because

TABLE 2
Shielding History Distribution by Distance from Hypocenter, City, and Study Group: Number (%) of Survivors with Shielding Histories

Distance category	Hiroshima		Nagasaki	
Life Span Study Cohort Survivors				
<1.6 km	10,460/14,183	(74%)	3,629/4,607	(79%)
1.6–2 km	5,273/12,546	(42%)	2,466/2,957	(83%)
2–3 km	464/19,136	(2.4%)	413/14,750	(2.8%)
>3 km[a]	39/16,119	(0.2%)	2/9,443	(0.02%)
Total	16,236/61,984	(26%)	6,510/31,757	(21%)
In utero study parents				
<1.6 km	262/480	(55%)	65/88	(74%)
1.6–2 km	203/358	(57%)	58/76	(76%)
2–3 km	36/414	(8.7%)	12/85	(14%)
>3 km[a]	2/667	(0.3%)	0/187	(0%)
Total	503/1,919	(26%)	135/436	(31%)
F1 mortality study parents				
<1.6 km	4,620/7,071	(65%)	2,545/3,177	(80%)
1.6–2 km	1,821/4,621	(39%)	1,448/1,683	(86%)
2–3 km	104/5,514	(1.9%)	221/5,000	(4.4%)
>3 km[a]	18/11,124	(0.2%)	0/8,326	(0%)
Total	6,563/28,330	(23%)	4,214/18,186	(23%)
Other[b]				
<1.6 km	0/351	(0%)	0/92	(0%)
1.6–2 km	0/470	(0%)	0/74	(0%)
2–3 km	0/2,421	(0%)	0/811	(0%)
>3 km[a]	0/5,532	(0%)	0/9,958	(0%)
Total	0/8,774	(0%)	0/10,935	(0%)
Full roster				
<1.6 km	13,182/18,566	(71%)	4,714/6,114	(77%)
1.6–2 km	6,024/15,007	(40%)	3,009/3,660	(82%)
2–3 km	563/23,636	(2.4%)	478/15,916	(3.0%)
>3 km[a]	81/27,835	(0.3%)	27/24,936	(0.1%)
Total[b]	19,850/85,044	(23%)	8,228/50,626	(16%)

[a] This table includes 44 persons with known distances >10 km who are not included in Table 1.
[b] See footnote to Table 1.

the energy released by an interaction is mostly deposited within a short but not infinitesimal radius of the location of the interaction. Due to equilibrium considerations, kerma is generally roughly equal to dose *except* near boundary surfaces between very unlike materials in which γ rays or neutrons have correspondingly different interaction rates per unit volume, such as between air and soft tissue, or soft tissue and compact bone (*19*). A very important concept is the so-called free-in-air (FIA) kerma. Free-in-air kerma can be thought of as the *maximum dose* that would be received in any of the tissues of an unshielded person at that location, i.e., just deep enough below the skin surface that the dose has equilibrated to the larger kerma of tissue (compared to air), but not so deep that there is any significant reduction in the number of γ rays or neutrons due to attenuation by the overlying tissue. Similarly, shielded kerma approximates the *maximum* dose that any of a person's tissues could receive in a shielded location. Additional details are given in ref. (*15*).

Where neutrons are concerned, the terms ‘‘fast’’ and ‘‘thermal’’ are frequently used. *Fast* neutrons, which are responsible for most of the neutron kerma in tissue, have high energy and in this case are *radiating*, i.e., generally moving in directions away from the bomb, whereas *thermal* neutrons have only the energy associated with thermal motion, i.e., they have come into thermal equilibrium with their surroundings and are moving in random directions. Some retrospective environmental dosimetry measurements of the A bombs involve thermal neutrons, which were generated near the sample by interactions of faster neutrons.

Kerma at a survivor's location or dose to a specific tissue is a function of the number per unit cross-sectional area (*fluence*) and energy distribution of γ rays and neutrons that reach that location or tissue. The energy-dependent coefficients used to convert fluence to kerma or dose, i.e., the rates at which neutrons or γ rays of a specified energy lose energy in, e.g., air or tissue, are called *conversion factors* (CF). The ratio of shielded kerma to free-in-air kerma at a shielded location is often referred to as a ‘‘transmission factor’’, in the sense that it relates to the portion of the free-in-air kerma that is ‘‘transmitted’’ through the shielding, although it is really portions of the fluences, not the kerma itself, that are being transmitted. Similar factors can be defined for the body's own self-shielding of internal organs and tissues by taking ratios of tissue and organ doses to shielded kerma.

As shielded kerma is defined as the product of free-in-air kerma and a shielding transmission factor, i.e., $\text{Kerma}_{\text{shielded}} = \text{Kerma}_{\text{fia}} \times TF_{shielding}$, and a particular organ dose D_{organ} is defined as the product of free-in-air kerma, a shielding transmission factor, and a body transmission factor specific to the organ, i.e., $D_{organ} = \text{Kerma}_{fia} \times TF_{shielding} \times TF_{organ}$, a given percentage change in any factor produces the same percentage change in shielded kerma and organ dose if the other factors are held constant. Throughout the following discussions, changes in shielding are quantified as changes in the associated transmission factor, which identifies the portion of any change in shielded kerma or organ dose that is due to a change in shielding, in terms of a change in a multiplicative factor.

Radiation transport and shielding calculations often refer to Monte Carlo methods, in which many individual hypothetical neutrons or γ rays are propagated by using interaction probabilities to choose the time, location and result of the next interaction, resulting in a set of ‘‘histories’’ for analysis. A technique called adjoint Monte Carlo reverses the process and works backwards from neutrons or γ rays arriving with specific energy and direction of travel at some ‘‘target’’ or ‘‘receptor’’ location of interest, back to some artificial boundary surface (coupling surface), or to a source. A different technique called discrete ordinates transport (DOT) in DS86 and discrete ordinates radiation transport (DORT) in DS02 was used to calculate the differential

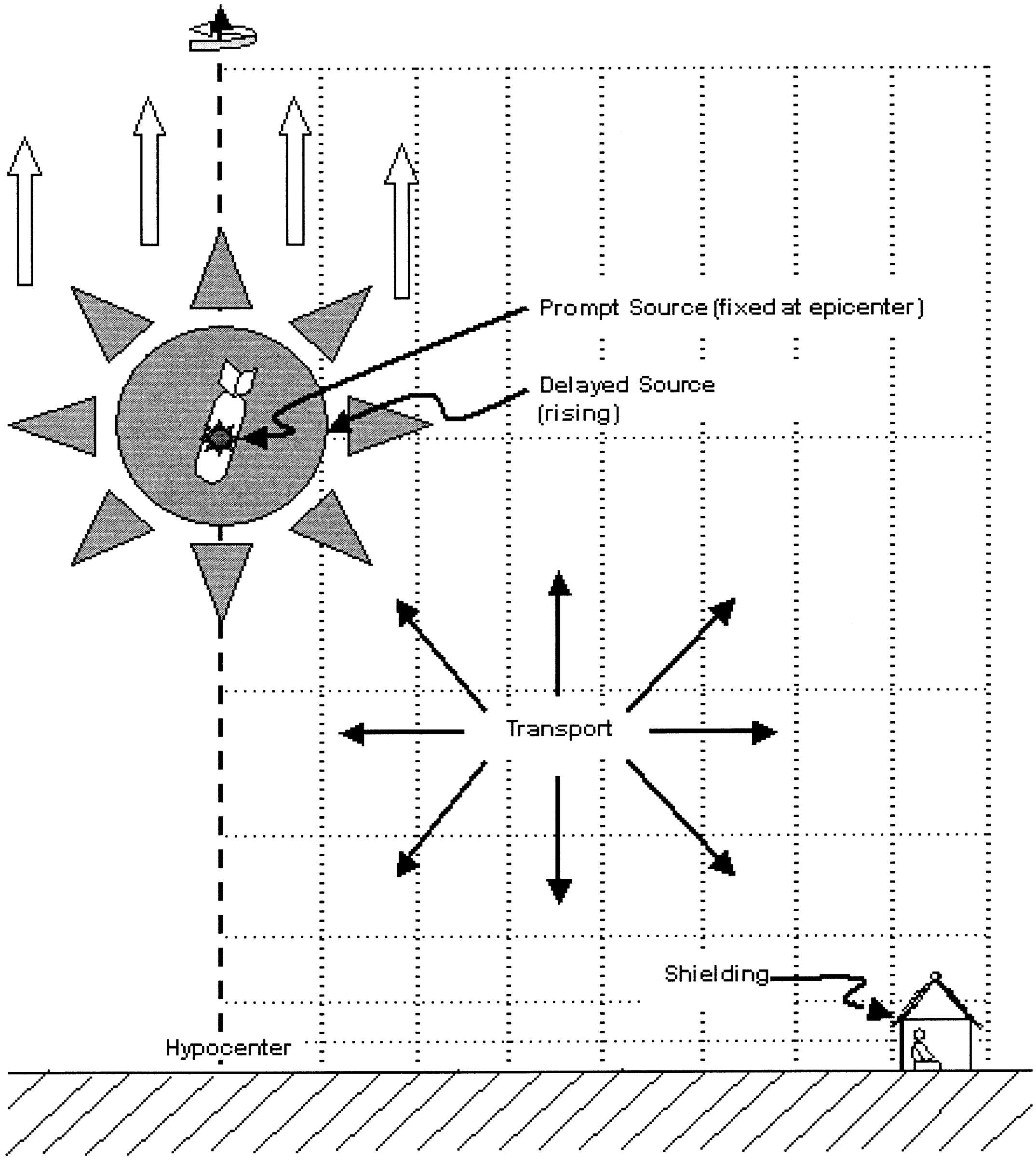

FIG. 2. A comprehensive atomic bomb survivor dosimetry system provides a source term, a transport model and shielding models.

fluences of neutrons and γ rays among artificial partitions in the materials near the bomb (lattice of dotted lines in Fig. 2), confined to a set of discrete directions expressed as angles.

Distance from the bomb to some point of interest on or near the ground is often specified as a ''ground distance'', which is the horizontal distance from the hypocenter directly below the bomb. In some cases, however, a more useful distance is the straight-line distance from the epicenter or ''burst point'' of the bomb to the same location of interest on the ground, which is called the ''slant range'' or ''slant distance'' and depends on the ground distance, the height of burst (HOB, vertical distance from the epicenter to the hypocenter), and the difference in elevation between the hypocenter and the location of interest.

There is one other potential source of longer-term radiation exposure from the bombs. This is *residual radiation* that resulted from the neutron activation of materials in the soil and structures near the hypocenter (induced radioactivity) or from local fallout of debris from the bombs. None of the dosimetry systems used at RERF attempt to provide individual estimates of the dose from residual radiation. The situation regarding residual radiation was most recently reviewed in the DS86 Final Report (*15*). As that report makes clear, doses from residual radiation are generally believed to be small and depend on so many unobserved and unobtainable factors that estimation is essentially impossible. For people who were not in the cities at the time of the bombings, the shielding history does include information about whether or not they entered the city within 30 days after the bombings (''early entrants'') or after 30 days (''late entrants'') as discussed above in the section on Populations of Interest, under ''RERF exposure status and dose master roster.'' This makes it possible to compare findings for early entrants to late entrants or to those who were in the city at the time of the bombings but were far enough from the hypocenter to have received negligible direct exposure.

HISTORICAL REVIEW OF ABCC-RERF SURVIVOR DOSIMETRY SYSTEMS

T57D

The first general survivor dosimetry system suggested for use at ABCC was a simple system called the Tentative 1957 Dosimetry (T57D), the first of two systems based primarily on measurements. It consisted of city-specific curves for γ-ray and neutron ''air doses'', which were equivalent to the later concept of free-in-air kerma, as a function of ground distance, and some simple curves that gave information on shielding provided by Japanese houses. Although the original T57D report gave burst heights (HOBs) of 606 m in Hiroshima and 500 m in Nagasaki (*20*), the HOBs generally associated with T57D were 580 m and 490 m, respectively (*16*). The yields were estimated at 18.5 kilotons (kt) in Hiroshima and 23 kt in Nagasaki. The ''York'' air dose curves used in T57D were based partly on theoretical considerations and partly on rudimentary consideration of the early atomic bomb tests. In the initial description of T57D it was indicated that the dose estimates were only accurate to within about a factor of two (*20*), while a later report (*21*) indicated that they were really only intended to provide ''order of magnitude'' estimates.

T57D provided simplified estimates of shielding based on the measurements made with two model houses during U.S. nuclear weapons tests carried out in 1957 as part of Operation Plumbbob. The report gave curves for estimating transmission factors for neutrons and γ rays as a function of slant penetration (defined as the distance along a ray from the bomb to the survivor, measured from the point at which that ray first enters the structure occupied by the survivor, i.e., the portion of the dotted lines between the survivor and the roof in the elevation view drawing ''C'' in Fig. 1).

The inadequacies of T57D, particularly the inadequacy of the characterization of the radiation source terms and the limitations of the shielding estimates, were recognized at the time of its introduction (*21*). Because of these concerns and the fact that efforts were under way to develop a more complete survivor dosimetry system, T57D doses were only used in a limited number of studies, and no systematic efforts were made to assign doses to large numbers of survivors.

T65D

The Tentative 1965 Dosimetry (T65D) system was the first dosimetry system used for serious dose computations (*16, 22*). Work on implementation of the T65D began in the mid-1960s and was largely complete by the end of that decade. T65D provides estimates of free-in-air kerma and transmission factors used to convert kerma estimates to shielded kerma estimates. The T65D dose estimates were recomputed in the late 1970s based on a change in the location used for the Nagasaki hypocenter (*23*) and a change in the estimated HOB; these revised dose estimates are sometimes referred to as T65DR estimates (*24*). They are not large departures from T65D, and in some cases they have been referred to as ''T65D'' doses despite this difference (*25*).

1. Free-in-air kerma

T65D γ-ray and neutron air dose (free-in-air kerma) estimates in each city are computed as simple functions of slant range with allowance for height above sea level in Nagasaki. These functions were based on weapons test data and the results of field experiments using a tower-mounted ''bare'' nuclear reactor experiment in Nevada (BREN) and other large γ-ray and neutron sources. They were partially corroborated by a limited set of early measurements of materials in Hiroshima and Nagasaki: γ-ray dose measurements of the thermoluminescence of quartz crystals in roof tiles and bricks (*26, 27*) and measurement of neutron activation by radiation counting of ^{60}Co in samples of iron and steel (*26*).

In addition to improvements in the characterization of the air dose curves, the yield and HOB estimates were changed to 12.5 kt and 577 m in Hiroshima and 22 kt and 507 m in Nagasaki (*16*). The yield and the corresponding dose estimates in Nagasaki were based on what were felt to be fairly straightforward comparisons to measurements of comparable devices in weapons tests, but the yield and dose estimates in Hiroshima were calculated differently due to the lack of comparable test weapons. The Hiroshima yield was estimated based on the average of several studies, including those of the blast overpressures that were measured by canisters dropped from spotting aircraft at the time of the bombing (*17*), and doses were calculated by estimating several related variables, some of which were measured in the experiments with radiation sources noted above. The height-of-burst and hypocenter values were tentatively re-estimated by ABCC based on a review of earlier studies, to allow publication of a tentative dosimetry system, which is one of the reasons that T65D, like T57D, was considered tentative. [A more definitive study of the hypocenter locations and HOB estimates was published in 1969 (*14*).]

The T65D free-in-air kerma equations have the form

$$K = \frac{K_0 \exp(-r/\rho)}{r^2}, \tag{1}$$

where r is the slant range, ρ is the ''relaxation length'' (change in distance corresponding to a 1/e reduction in the exponential), and K_0 is an ''extrapolated source term'' for free-in-air kerma that gives the correct values for (1) at distances on the ground that are greater than a couple of relaxation lengths from the epicenter. The T65D relaxation lengths were 198 m for neutrons in both cities, 250 m for Hiroshima γ rays, and 350 m for Nagasaki γ rays, with K_0 estimates in 10^8 Gy m^{-2} of 8.7 and 1.3 for neutrons and 3.45 and 2.75 for γ rays, for Hiroshima and Nagasaki, respectively (*16, 22, 28*).

2. Shielding by structures and terrain

T65D includes methods for dealing with several types of external shielding based on computation of γ-ray and neutron transmission factors from information about the survivor's shielding at the time of the bombing.

Special efforts were made to develop transmission factor estimates for survivors exposed in houses, tenements or other light wooden structures since this was the most common shielding situation. Data from dosimeters inside and outside Japanese-house-like structures built at the Nevada weapons test site were used to develop linear regression models for the transmission factors. Since nine predictor variables were selected for the model to be used in T65D, this model and its later derivatives are generally called ''nine-parameter'' models (9P). The variables were floor number, slant penetration (as defined above under T57D), number of internal front walls, number of internal lateral walls, presence or absence of a frontal (external) shield, frontal shield size, presence or absence of a lateral (external) shield, height above floor, and distance from an unshielded window in the direction of the bomb (*16, 17*). (A ''frontal shield'' in this case refers to any nearby structure, separate from the one occupied by the survivor, in the direction of the hypocenter.) These nine parameters along with information on the type of structure were coded from the shielding history drawings.

Since most distally exposed survivors and many proximal survivors did not have shielding histories, it was necessary to devise alternative methods to compute shielded kerma for people without complete shielding information. Two methods were used to deal with this problem. First, T65D shielded kerma was taken as equal to free-in-air kerma for survivor locations beyond 1,600 m ground distance in Hiroshima and 2,000 m in Nagasaki. Second, average ''house'' transmission factors were used for all proximal survivors without detailed shielding information who were known to have been exposed in houses, tenements or similar structures: 0.914 and 0.813 for γ rays and 0.316 and 0.351 for neutrons in Hiroshima and Nagasaki, respectively.

The shielding histories revealed that a number of survivors who had been outside also had some degree of shielding by nearby buildings or terrain. In these cases a spherical coordinate projector, or globe, was used with a physical scale model of a survivor's surroundings to determine the portions of solid angle in various directions that were blocked by nearby hills or buildings. The T65D kerma was then determined by allowing for these blocked angles. This approach generally came to be called the ''globe'' method.

About 13% of the proximal survivors in Nagasaki were working in factories at the time of the bombings. Because these workers were typically closer to the hypocenter than other proximal survivors in Nagasaki with shielding histories, they account for a large portion of high-dose survivors in Nagasaki (using DS02 estimates, about 25% of survivors with shielded kerma >1 Gy). Over the years, extensive efforts were made to obtain information on the shielding for factory workers, including the specific factory building in which a person was working, his or her location in that building, the presence of benches and heavy equipment such as lathes and presses at worker locations, and the structural shape, dimensions and building materials for each factory building. For the 815 people exposed in factories of two general building types, it was decided that shielded kerma would be taken as 0.9 times free-in-air kerma for those in buildings with slate saw-tooth-shaped roofs who were not behind heavy equipment and equal to free-in-air kerma for those in buildings with galvanized iron roofs and not behind heavy equipment, while doses would not be assigned to other factory workers because of the impracticality of shielding calculations for heavy equipment and various other types of building construction.[2]

T65D shielded kerma was also taken as equal to free-in-air kerma for all survivors who reported that they were outside without external shielding. Survivors who were reported to have been in concrete buildings (791 people) or other heavy structures were a difficult problem. Doses were calculated using a globe method for about 200 survivors with well-documented information about their positions inside particular buildings (*29*). Although these doses were used primarily in the genetic studies, there was concern about the complexity of the associated shielding calculation and the great sensitivity of the result to the survivor's exact location with respect to windows, doors, etc. Apart from persons outside and in the open or shielded by nearby structures, or inside light wooden buildings, factories or concrete buildings, shielding was reviewed for the remaining survivors, and expert judgment was used to assign doses to 5,922 of the 8,952 people in the T65D roster with other types of shielding.

3. Organ doses

The T65D system did not explicitly provide organ doses, and virtually all T65D analyses were based on shielded

[2] ABCC Department of Statistics procedure ''C.D. # 499: Code for provision of transmission factors of radiation by globe work or by application of air dose,'' 1970.

kerma estimates. However, in response to concerns about the adequacy of the T65D assumption of a relatively uniform distribution of doses across tissues, efforts were begun to develop more accurate organ-specific dose estimates. These efforts resulted in the development of γ-ray and neutron body transmission factor estimates for a number of tissues (*30*, *31*), including trimester-specific fetal dose transmission factors. Although organ doses based on these types of calculations were not used in any major analyses at ABCC/RERF, they were used by the BEIR III Committee (*32*) and figured prominently in the controversy surrounding leukemia and the relative biological effectiveness (RBE) of neutrons that led toward the development of DS86, as described in the next section.

DS86

1. Motivation

An important step leading to the DS86 reassessment effort was a presentation by H. Rossi in 1976 to the U.S. National Council on Radiation Protection and Measurements (NCRP). Rossi and A. Kellerer had raised issues in 1974 in an analysis of leukemia risk from neutrons in atomic bomb survivors, based on kerma in air outside the body (*33*). Rossi had recalculated the risk based on new models for the human body's self-shielding of neutrons that showed a dose to bone marrow much less than the kerma in air (*34*). He suggested that the reduced dose and an observed city difference in leukemia risk estimates between Hiroshima and Nagasaki, related to a difference in the ratio of neutron to γ-ray dose in the two cities, implied that neutrons were more biologically effective (risk per unit dose) than previously thought. Therefore, Rossi recommended that the NCRP increase its value for the relative biological effectiveness (RBE) of neutrons by an order of magnitude. This was repeated in a 1978 paper by Rossi and Mays (*35*) as a recommendation to reduce the maximum permissible dose for neutrons, and the NCRP's consideration of the ensuing controversy was summarized in 1980 in NCRP Statement No. 5, ''Dose Limit for Neutrons'' (*36*).

One immediate response of the NCRP to Rossi's talk was to set up a Task Group to investigate the accuracy of the T65D system (*37*, *38*). Among the major concerns of the Task Group were that (1) the T65D kermas for neutrons and γ rays were much lower per kiloton of bomb yield than published data from a variety of other weapons and (2) the T65D kermas for γ rays decreased at a much greater rate with distance from the hypocenter in Hiroshima than in Nagasaki. After considerable study, the Task Group concluded that the material in the open literature was insufficient for a determination of the accuracy of the T65D system (*38*).

The Task Group recommended that a person with the proper security clearance should complete the review using both classified and unclassified sources of information. They hoped that after this was done enough information could be made publicly available to provide a secure foundation for radiation recommendations based on data from RERF studies. The U.S. Department of Energy responded by funding G. D. Kerr of the Oak Ridge National Laboratory (ORNL) to start such a study in 1979. Kerr not only included classified data in the study; he also began incorporating much new data that had not been applied yet to the atomic bomb dosimetry. Use of these newer data led to other investigators from ORNL, Los Alamos National Laboratory (LANL), Science Applications International Corporation (SAIC), and R&D Associates being drawn into the study.

A key piece of information in the newer studies of A-bomb dosimetry was provided by researchers at LANL (*39*). In the mid-1970s, researchers at LANL took advantage of advances in computing capabilities over the years since the development of T65D to calculate the source terms for the Hiroshima and Nagasaki bombs. The results suggested that the Hiroshima bomb produced significantly fewer neutrons than suggested by the T65 dose estimates. Other aspects of the A-bomb radiation calculations also came under scrutiny, and it was realized they needed improvement. For example, Scott at SAIC[3] showed that previous estimates of the γ radiation from fission products in the fireball were not as accurate as had been thought, and Marcum at R&D Associates[4] raised questions regarding the accuracy of the shielding by houses and other light structures. The results of the review by Kerr and the contributions of others to this review can be found in ref. (*40*).

Independently of Kerr and the NCRP Task Group, researchers at the Lawrence Livermore National Laboratory (LLNL) undertook a study. Their study was also prompted by the heightened concern due to the Rossi and Mays paper (*35*) that recommended a 10-fold increase in the RBE for neutrons. Loewe and Mendelson (*41*) reported neutron doses considerably lower than the T65D values, and the results of this study were used by Straume and Dobson (*42*) to publish data to judge the effect of the revised dosimetry on the interpretation of radiation risk estimates derived from RERF studies.

In the spring of 1981, the NCRP cosponsored with the North American Late Effects Group a ''Symposium on A-bomb Radiation Dosimetry'' at the 29th Annual Meeting of the Radiation Research Society in Minneapolis, MN (*43*). The attendant publicity in both the scientific and lay press brought the situation to the attention of interested scientists and political representatives of the Japanese and U.S. governments. The U.S. Department of Energy organized a symposium on atomic bomb dosimetry (*44*) and initiated a binational program to re-examine all aspects of

[3] Letter from W. H. Scott, Jr., of SAIC, to G. D. Kerr, ORNL, May 5, 1981.

[4] Letter from J. Marcum of R&D Associates, to G. D. Kerr, ORNL, May 15, 1981.

the dosimetry. This led to the development of a new dosimetry system, DS86. The work of DS86 was done by many investigators, most forming a working group led by Robert Christie of the California Institute of Technology as chairman. A senior review panel was appointed by the National Academy of Sciences with a former President of the Academy, F. Seitz as chairman and included some of the original members of the NCRP committee. This group supervised the working group and approved the use of DS86; they produced their own brief summary report of DS86 (*45*) as also noted in ref. (*15*). After that NAS-NRC had a continuing committee on the Dosimetry for RERF that was not disbanded until after the completion of a report on the status of the dosimetry in 2000 (*46*).

The new system designated as the Dosimetry System 1986 or DS86 was based on the best contemporary understanding of the source term, radiation transport, and shielding (defined below in this section) and exploited the latest computational methods. The DS86 Final Report (*15*) is available on the RERF website at http://www.rerf.jp/shared/ds86.ds86a.html. In 1988, the basic DS86 system was extended as noted and approved by the NAS-NRC Committee on Dosimetry for RERF to include survivors in Nagasaki factories. The following discussion refers to this final version of the DS86 system (*47*).

2. Free-in-air fluences and kerma

In contrast to earlier methods of adapting the empirical results of dosimetric measurements in model structures irradiated by bombs or bomb-like radiation sources, DS86 involves a more complete characterization of the radiation components that contribute to the survivor dose estimates. The basic features of the DS86 (and DS02) dosimetry systems are indicated in Fig. 2. These include a description of the *source term* and models that modify the source to account for the effects of radiation transport through air over ground (*transport model*) and shielding in the vicinity of the survivor (*shielding models*). The source term describes the energy and angular distributions of γ rays and neutrons emanating from the explosion and fireball, while the transport model describes how these distributions are modified as the radiation propagates in air over ground. The shielding models further adjust the distributions to account for the effects of shielding provided by buildings, terrain and, in the case of organ doses, the survivor's own body. In recent dosimetry systems (DS02 and DS86), radiation exposures are assumed to be symmetrical about an axis from the hypocenter to the epicenter, and transport in air is modeled in a two-dimensional cylindrical geometry over flat ground, as indicated by the grid shown in the drawing. Earlier systems (T57D and T65D) did not explicitly consider these details; rather they provided simple equations (or graphs) that described how γ-ray and neutron ''air doses'' varied with distance and they made use of empirically derived transmission factor estimates to account for the effects of shielding.

The neutrons and γ rays contributing to survivor doses arise from several sources. For free-in-air kerma, these components include: (1) *prompt* neutrons and γ rays emitted in fission reactions in the bomb and γ rays produced by fast neutron interactions in the materials of the bomb, the air around the bomb, and the ground underneath the bomb, and (2) *delayed* neutrons and γ rays emitted by the decay of radioactive atoms in the fireball.

The prompt radiation source is primarily localized to the bomb materials and the air within about 200 m of the bomb. It is stationary and short-lived (microseconds to tens of milliseconds)—the fission chain reaction terminates within microseconds, and the radiations propagate outward at close to the speed of light, ~300 m per microsecond, whereas mechanical energy dispersion is limited by the speed of shock waves traveling at the speed of sound, i.e., of the order of millimeters per microsecond. A Hiroshima-type bomb emits its prompt, primary radiations (directly from the fission of uranium or plutonium) before it begins to physically explode to any visible extent, and the prompt emission is complete before the fireball is substantially formed. (A Nagasaki-type bomb begins to explode visibly as the explosion to compress the uranium or plutonium is initiated, but the prompt radiations are emitted in the same small fraction of a second during and immediately after the nuclear chain reaction.) The delayed source in both bombs arises from the radioactive fission debris (fragment nuclei of fissioned uranium or plutonium and neutron-activated bomb materials) associated with the fireballs. Because the Hiroshima and Nagasaki bombs were air bursts with HOBs far above ground at ~0.5 to 0.6 km, materials from the ground were not entrained in the fireballs, which quickly began moving upward as a result of thermal convection, having an effective duration of a minute or less at altitudes where they contributed significant dose to survivors. Additional detail is given in, e.g., Chapter 3 of the DS86 Final Report (Table 1 of that chapter and the associated discussion).

Prompt radiation transport in DS86 is modeled in the simple geometry illustrated in Fig. 2 (i.e., a two-dimensional model of the air and ground, including air density and humidity relative to altitude), assuming cylindrical symmetry, using the Monte Carlo and DOT methods. A separate transport model is necessary for delayed radiations because of the size, shape and motion of the source, and the fact that the evacuation of air behind the blast wave creates time- and space-dependent changes in air density that must be considered. DS86 includes a database that provides angle-dependent fluence estimates for 21 neutron energy groups and 37 γ-ray energy groups for each of the four free-in-air fluence components (prompt and delayed γ rays and neutrons) at 25-m intervals out to a distance of 2,500 m from the hypocenter at various heights above the ground. The system uses energy-dependent conversion factors to convert free-in-air fluence values to free-in-air kerma estimates as an intermediate output. Linear interpolation on the logarithms of the 25-m values is used to provide estimates that correspond to the recorded survivor distances, giving free-in-air kerma components directly for all survivors who were within 2.5 km of the hypocenters at the time of the bombings.

3. Calculation of shielded fluences

The transported neutrons undergo many more fast interactions per unit volume in solid materials near the survivor, and in the survivor's own body, than in air, producing additional γ rays. These constitute additional sources and related components of γ-ray fluence and kerma, corresponding to prompt and delayed neutrons interacting with shielding materials (house, etc.) and the tissues of the body, e.g., ''shielding prompt gammas'', ''shielding delayed gammas'', ''body prompt gammas'', and ''body delayed gammas''. Since these depend on the size, shape and composition of the shielding, or the size and shape (i.e. posture) of the survivor's body, they are calculated as separate components in the DS86 and DS02 systems.

As a useful simplification it is often convenient to group similar types of radiation, such as all of the γ-ray dose components or all neutron dose components, together. It is also helpful, and at times essential, to summarize the effect of shielding by structures and terrain or from the survivor's body in terms of transmission factors (TFs) as described above in the section on Basic Concepts and Definitions for the various specific components. Averages of TFs calculated for cases with full, coded shielding information can be used to convert free-in-air kerma to shielded kerma, or shielded kerma to organ dose in situations lacking sufficient detailed shielding information to calculate the related fluences. Figure 3 provides a schematic representation of various aspects of atomic bomb dosimetry and illustrates some of the simplifications that are sometimes made in computing kerma and dose estimates. Fluences are calculated at three levels: ''free in air'', at a shielded location, and inside the organs of a survivor's body (Fig. 3a). The last of these, ''organ fluences'', are used to calculate dose to individual organs using energy-dependent conversion factors. Figure 3b illustrates the relationships involved in using conversion factors to obtain intermediate values of kerma, both free in air and in shielded locations, and in using ratios (kerma to kerma and kerma to dose) to define transmission factors. In the core DS86 system supplied to RERF, shielded fluences and organ fluences are calculated and shielded kerma and organ doses are provided for survivors with three types of shielding: houses and other light structures for which coded shielding data including the ''nine-parameter'' variables were available, house and terrain shielding for which globe data were available, and selected Nagasaki factories, as well as for survivors known to have no external shielding.

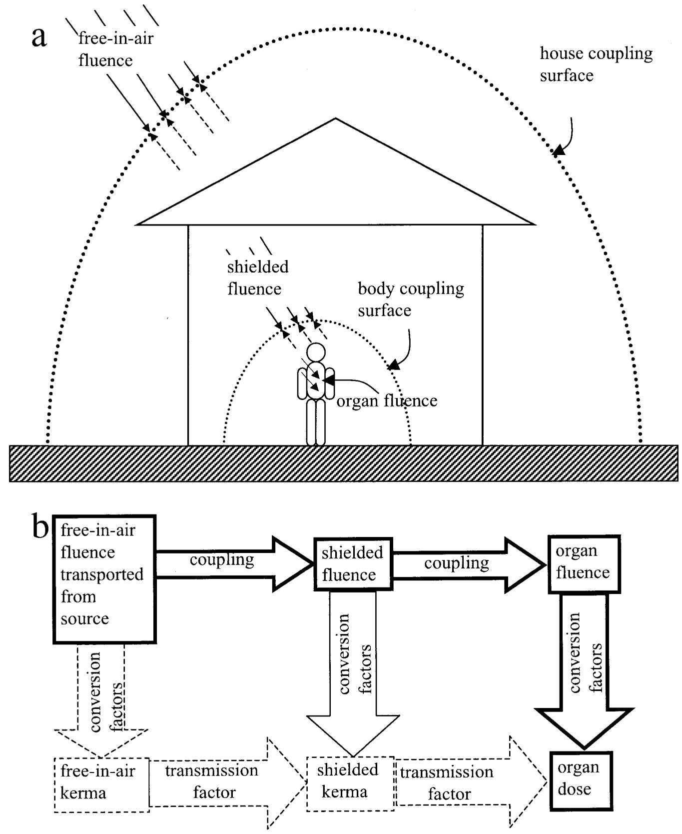

FIG. 3. Panel a: Physical schematic of fluences calculated in DS86 and DS02 and the surfaces for forward-adjoint Monte Carlo coupling. Fluences for only one of 240 angular directions are depicted. Forward fluences are solid arrows and coupled adjoint fluences are dashed arrows. Panel b: Computational schematic of dosimetric quantities calculated by DS86 and DS02. Calculation of organ doses for survivors with full coded shielding information proceeds by the pathway in bold outline. Conversion factors, which are energy specific, can also be used to calculate free-in-air and shielded kerma for the same survivors, establishing transmission factors as ratios of shielded to free-in-air kerma and organ dose to shielded kerma. Averages of these transmission factors can be used to calculate doses for survivors with less shielding information, via the pathway in dashed outline.

DS86 shielded fluences are calculated using an adjoint Monte Carlo method, in which representative structures are modeled in three dimensions and individual hypothetical neutrons and γ rays with randomly selected angles and energies are ''started'' at a point of interest inside the structure and followed backward in time until they reach (''leak'' through) an artificially defined coupling surface that surrounds the structure (outer dotted line in Fig 3). The energy and angular distribution of these leaking particles are summarized as a ''leakage'' table of *adjoint fluences* that establishes a numerical relationship between the *forward fluences* incident on the coupling surface from outside and the shielded fluences that would result at the point inside the structure.

Due to computational and resource limits (both in the 1980s and today), it is not possible to develop an individual shielding model and carry out a customized computation for each survivor. Also, for similar reasons, the developers of DS86 decided to base all shielding computations on previously coded information instead of returning to extract additional information from the original shielding history drawings. They therefore devised two detailed house models that could be used to represent the full range of survivors' individual shielding situations, so that the Monte Carlo results from the models could be applied to the coded survivor data.

4. House shielding

DS86 makes use of two house-model clusters—a six-house cluster and a tenement-style cluster—designed to be broadly representative based on a review of a sample of survivor shielding histories. Adjoint Monte Carlo computations were carried out for a total of 21 representative locations inside houses of the six-house cluster and 60 inside locations in the tenement model, including a sample of second-story locations.

For any particular survivor, that survivor's house-type variable and four of the 9P variables defined above in the section on T65D (slant penetration, floor number, frontal shielding and proximity to a window in the direction of the bomb) are used to choose an appropriate location in one of the two model clusters. The stored leakage table for this location is then linked to the free-field fluence data for the correct distance, rotated to the correct orientation, to provide shielded fluence estimates that can be used to compute shielded kerma or further modified to produce organ fluences.

The transmission factors for γ rays calculated by DS86 for wooden houses were considerably less than those for T65D, largely because of a reduction in the component of shielded γ-ray kerma produced by interactions of neutrons in the materials of the house (''shielding n-gamma''). This related to a difference in the transported neutron fluence that had produced the ''shielding n-gamma'' part of the γ-ray doses measured in model houses at the Nevada Test Site compared to that calculated for the moister air of Hiroshima and Nagasaki by DS86 (*15*). For example, the overall average γ-ray TF obtained with DS86 fluences and shielding for persons in nine-parameter wooden houses in the current RERF data set is 0.46 in Hiroshima and 0.49 in Nagasaki, compared to the values of 0.91 and 0.81 noted above for T65D.

5. Shielding by nearby structures and terrain (globe method)

The globe method for calculating shielding of persons outdoors in the vicinity of buildings or other structures providing heavy shielding was adapted for use in DS86 by compiling leakage tables for a number of positions outside the buildings in the house model clusters. These tables are indexed by an estimate of the proportion of the neutron (not γ-ray) fluence that would not be blocked due to the shielding described by the globe data, and that index is used to select a model calculation.

Most (3,731 of 4,433) of the survivors with globe data were shielded by nearby houses. About 8% of the survivors with globe data for nearby houses were also shielded by local terrain features, i.e. small hills. In the DS86 report, the shielding provided by small hills for survivors in the open was calculated in the same manner as the globe shielding for houses described above, but using a model hill instead of model house clusters. The terrain model in the DS86 report was never implemented by RERF. In 1988 RERF received a new terrain model for Nagasaki[5] that took more account of the hilly terrain there. In this model the horizon is described by five elevation angles, in the direction of the hypocenter and at 45° and 90° to the left and right thereof, that are coded in the database for survivors, as shown in Fig. 4. The angles are used to choose a representative terrain-shielding leakage table from a database of adjoint Monte Carlo calculations for a set of terrain models consisting of combinations of basic geometrical shapes with appropriate properties, and that leakage table is used to further modify the globe-adjusted fluence. As will be noted below, this method of terrain adjustment is applied to many more survivors in the current (DS02) dosimetry system, because it has been applied to account for the shielding provided by some much larger hills at greater distances.

6. Nagasaki factory shielding

The 1988 supplement to DS86 mentioned in the previous paragraph also modeled two buildings designed to be representative of major factory buildings in Nagasaki and calculated shielded fluences for a number of locations inside each building. Because these models suggested minor dependence of the transmission factor on location within the building (coefficient of variation ~10%), and survivor data had not then been coded to indicate location within the building, a decision was made to use leakage tables averaged over locations within a building. About 80% of the Nagasaki factory workers were in buildings of the type represented by the models. As with T65D, dose estimates were not computed for factory workers believed to have been located near heavy equipment.

7. Organ doses

To calculate energy-specific fluences in the various tissues and organs from shielded fluences, DS86 uses an adjoint Monte Carlo method similar to that for structures, but with models of the human body instead of houses or terrain. Leakage tables from the body models are coupled at a surface surrounding the body (inner dotted line in Fig. 3a) to

[5] M. L. Gritzner and W. A. Woolson, ''Additions to DS86: Factory Workers, Terrain-shielded Survivors,'' provided to RERF by Science Applications International Corporation in 1988.

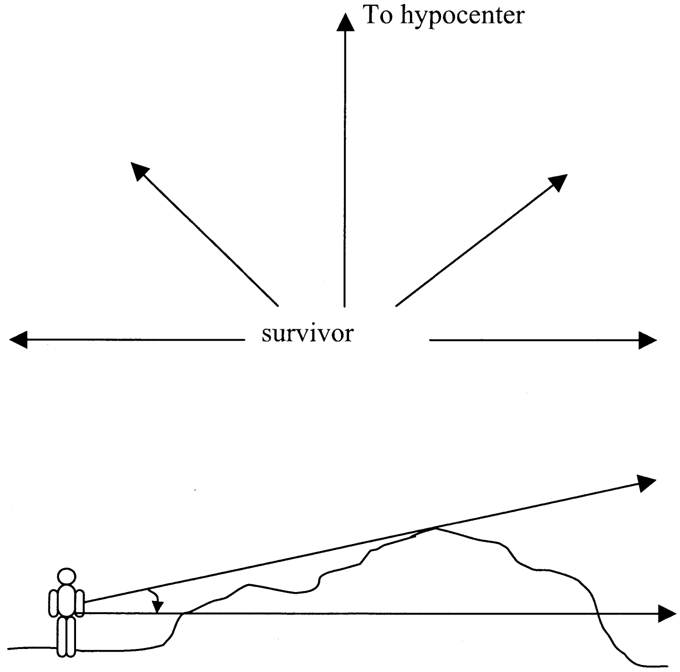

FIG. 4. Specification of terrain elevation angle in five azimuthal directions centered on the direction to the hypocenter, in plan view (top) and elevation view (bottom).

appropriate shielded fluences, or, for survivors who are in the open and unshielded, the appropriate free-in-air fluences. Organ doses are then calculated from organ fluences using conversion factors as described in the above section on Basic Concepts and Definitions. Standardized human ''phantoms'' (physical models of the human body made of artificial materials) were developed based on a study of anthropometric data for the Japanese population of 1945. They were analyzed extensively, resulting in detailed anthropomorphic shapes with specified elemental compositions, including internal tissues and organs, for three age ranges (''infants'' aged 0–2, ''children'' aged 3–11, and ''adults'' aged 12 or more), three postures (standing, kneeling, prone or unknown), and four orientations with respect to the direction to the hypocenter (anterior, posterior, lateral or unknown). DS86 provides organ dose estimates for the following 15 organs:

Bladder	Brain	Breast	Colon	Eye lens
Lung	Liver	Marrow	Ovary	Pancreas
Skeleton	Stomach	Testes	Thyroid	Uterus

In addition to these organs, skin dose is taken to be equal to shielded kerma. In contrast to T65D, DS86 does not include fetal dose estimates. In general the fetal dose is taken to be the same as the dose to the mother's uterus.

More information about the history of T57D, T65D, T65DR and DS86 is given in, e.g., refs. (*25*) and (*48*), in addition to the particular reports corresponding to those systems as cited in the preceding sections.

DS02

Motivation

The primary motivation for DS02 was a crisis of confidence in the accuracy of DS86, related to what has been called the ''neutron discrepancy'' regarding the Hiroshima bomb. This concern arose from measurements of thermal neutron activation in materials present at the time of the bombings and resulted in speculation and controversy about the possibility that neutrons may have played a larger role in the observed health effects in Hiroshima than suggested by analyses based on DS86. Its resolution represents a step forward in the technology of both the computational basis of radiation dosimetry and the related development of retrospective radiation measurements in environmental materials.

The controversy as generally perceived did not pertain to measurements of γ-ray dose. Methods for measuring γ-ray doses by thermoluminescence had been developed by Japanese researchers beginning in the 1960s, concomitantly and sometimes collaboratively with techniques developed in archaeology for the dating of ceramic artifacts (*27*), and were extensively refined and elaborated in the creation of DS86 (*49*). The general conclusion was that the agreement between measurement and calculation was good for the DS86 calculations and measurements of γ-ray dose (*15*).

The measurement of thermal neutron activation as a surrogate of neutron fluence was in an earlier stage of development when the DS86 Final Report was written. That Report ended its chapter on neutron measurements with the statement that ‘‘the conclusion of this chapter . . . must be that the neutron doses are in doubt until further work is done.’’ The concern in DS86 focused on Hiroshima, particularly on a plot of ratios of measured to calculated thermal neutron activation (^{60}Co) as a function of distance, which suggested that measured values were below calculated values near the hypocenter, crossed over at some middle distance, and became increasingly larger than calculated values with increasing distance. Even as the DS86 Final Report was being prepared, scientists were attempting to investigate the problem with additional measurements. ^{60}Co and ^{152}Eu were measured by refined radiation counting with new techniques for chemical enrichment of samples in the late 1980s and 1990s (*50–53*), and a new technique was devised to measure another thermal neutron activation product, ^{36}Cl, by accelerator mass spectroscopy (AMS) (*54*). By the mid-1990s, papers alleging a potentially serious discrepancy in neutron dose estimation had aroused considerable concern (*55*, *56*). These papers suggested, in fact, that the calculated DS86 neutron doses at Hiroshima were too small by a distance-dependent factor ranging up to as much as 10 or more at a ground distance of 1.5 km.

Because the radiation transport methodology used in DS86 had been checked in nuclear weapons tests in the U.S. and elsewhere, whereas the Hiroshima bomb was unique in its design and had never been tested, there was also a common supposition that the discrepancy in Hiroshima must be due to some aspect of the source term. Based on the preceding concepts, various conjectures were made around the idea that the Hiroshima weapon might have functioned in an unforeseen manner, with some kind of a loss of integrity in the bomb case, prior to the fission chain reaction, that would have allowed fission neutrons to emerge unattenuated and unmoderated in energy in some directions, leading to larger fluences at longer distances. This was commonly referred to as a ‘‘crack’’ model for the Hiroshima bomb (*56*, *57*).

In response to this concern and many others, such as those raised by the NAS-NRC Committee on Dosimetry for the RERF (*46*), the U.S. Department of Energy appointed a U.S. working group for the reassessment of atomic bomb radiation dosimetry. This group worked collaboratively with a similar Japanese group appointed by their Ministry of Health (Education and Welfare) to form a Joint Bi-national Working Group co-chaired by Robert Young and Hiromi Hasai, which resulted in the creation of DS02 (*46*, *58*, *59*).

Improvements in DS02

The DS02 effort involved recalculation of both the source term and the radiation transport, which should greatly improve confidence in these aspects, particularly in light of the thorough consideration given to various possible sources of error, discussed briefly below. The working groups evaluated the agreement between calculations and all measurements to date in great detail and decided to change the estimated yield and height of burst in Hiroshima, as described below. But the most important contribution to resolving the ‘‘neutron discrepancy’’ at distances most relevant to survivors came from new measurements and a better understanding of previous measurements.

1. Source term calculations

The DS02 working group initially considered evaluating the source term empirically by working backward from the measurements using an adjoint Monte Carlo calculation, but it was demonstrated that the measurements did not contain enough energy spectrum and spatial information to allow a useful reconstruction of the angle and energy profile of the neutrons escaping the bomb. The working group also considered alternative hypotheses about the mechanical functioning of the Hiroshima bomb, but the weapons experts stressed that, to have achieved a yield in the range that was realized, the weapon must have worked as designed. The new source term calculation was repeated for various possible starting times of the fission chain reaction relative to the mechanics of the bomb, improving information about the range of possible yields and the implausibility of a breach in the integrity of the bomb case before the fission starting time. Modern supercomputing capacity enabled detailed simulation of the entire bomb structure, rather than the type of simplified models that were used in DS86. These calculations were done with more input data and more spatial and temporal resolution than DS86 and were carried out to one full second after the beginning of the fission chain reaction, much longer than the DS86 calculation.

2. Transport calculations

As in DS86, the Monte Carlo transport calculations in DS02 were cross-checked with discrete ordinates radiation transport (DORT) calculations. All calculations were performed with the newest available physical constants for the propagation of the neutrons and γ rays and finer energy groupings than had been used for DS86.

The Hiroshima bomb had a cylindrical symmetry about the axis from its nose to its tail, unlike the roughly spherical symmetry of the Nagasaki bomb, and more radiations were emitted sidewise through the ‘‘waist’’ of the bomb than through the angles involving the nose; moreover, the bomb was tilted at an angle of about 15° from the vertical at the time of explosion (*60*, *61*). A three-dimensional, forward Monte Carlo simulation involving 100 billion complete particle histories confirmed that fast neutrons had no appreciable asymmetry beyond about 1,000 m, and thermal neutrons had virtually no asymmetry even near the hypocenter. This in turn confirmed that a two-dimensional transport calculation in a cylindrical geometry was adequate for survivor dosimetry because bomb tilt does not affect doses at survivor distances. Although bomb tilt corrections themselves are not used in the dose computation, it was important to validate this assumption by calculation, and a bomb tilt correction was important for comparisons of measured to calculated values for fast neutrons near the hypocenter in Hiroshima.

The DS02 development also included bounding calculations to assess the effects of various aspects of the materials at the Earth's surface, or ''ground'', on the propagation of radiations, whereas DS86 was strictly confined to ''wet Hiroshima soil'' considered as a perfectly flat planar surface of one chosen uniform composition. Again, these calculations are not used directly in the calculation of survivor doses but helped the working group understand some of the sources of variation in environmental measurements, particularly of thermal neutrons.

3. Environmental measurements

New developments in environmental measurements of both γ-ray thermoluminescence and neutron activation played a central role in the development of DS02. Investigators have made numerous thermoluminescence and thermal neutron activation measurements since the publication of DS86, including some published for the first time (*59*). The developers of DS02 summarized all thermoluminescence measurements to date and provided new analyses of background and uncertainty issues, in addition to revising and extending sample-specific transmission factors to all measurements reported by 2003, including some post-DS86 measurements and some not calculated in DS86. DS02 is also corroborated by measurements of fast neutrons using new techniques based on activation of copper to produce ^{63}Ni (*59*), the first fast neutron measurements since the 1945 measurements of ^{32}P in sulfur, which could never be repeated because of its short half-life of 14.3 days. Old and new thermal neutron measurements were reanalyzed extensively in developing DS02, and a key role was played by a series of new, ultra-low background measurements of ^{60}Co and ^{152}Eu. Research groups in Japan and Germany contributed measurements of ^{36}Cl, and several designed intercomparison studies were undertaken (*59*).

4. Changes in Hiroshima bomb parameters and overall changes in (free-in-air) kerma

When it became clear that neither the new source term calculations nor the new transport calculations were likely to explain the discrepancy of high-precision neutron measurements near the hypocenter in Hiroshima, the working groups were compelled to consider the ''bomb parameters'', particularly the estimated bomb yield and height of burst, whose effects on dose as a function of distance are interrelated. The yield and height-of-burst values implied by the measurements were considered in light of all of the other lines of evidence bearing on those parameters, such as the yield range implied by the new source term calculations, and all of the older data relating to sightings, shadows of thermal burns, blast canisters and so forth. The Joint Binational Working Group decided to make a change in both yield and HOB, which was a key improvement in the agreement of measurements and calculations at short distances.

The disagreement between measured and calculated values at distances exceeding approximately 1 km is a different matter. In brief, this discrepancy was largely due to the fact that measured values are more variable than was previously appreciated, and some of them contained artifacts unrelated to thermal neutron activation by the bomb fluences. Additional discussion of this topic is given in the detailed DS02 documentation (*59*) and RERF Update (*62*).

The DS02 free-in-air kerma values as a function of distance from the hypocenter are shown in Fig. 5, and the percentage changes from DS86 are shown in Fig. 6. In this, as in the figure, tables, and text below, the DS02 percentage change from DS86 is defined as 100((DS02 − DS86)/DS86) and is therefore undefined for situations in which the DS86 value was either assigned as zero or undefined.

In Hiroshima, the yield was increased from 15 kt to 16 kt, which produces a proportional, essentially uniform increase of about 7% in all fluences if all other parameters are held constant. In addition, the height of burst (HOB) was raised from 580 m to 600 m, which tends to decrease the fluences near the hypocenter but has a diminishing effect at longer ground distances, where the slant distance from the epicenter to a point on the ground is less dependent on the height of burst. The most important other factor in Hiroshima is an increase in the prompt γ-ray fluence per kiloton of yield in the source term. The reasons for this increase involve the longer interval of one full second in the nuclear explosion that is calculated in DS02, the inclusion of higher-energy γ rays (between 10 MeV and 20 MeV) not considered in DS86, newer physical constants for probabilities of neutron interactions, the inclusion of more metal parts in the model of the bomb, and technical developments in the modeling of particle interactions in the bomb materials. The first three of these factors all have an important relationship to the production of γ rays by the interaction of neutrons with the nuclei of nitrogen atoms in the air around the bomb. The net change overall is that the DS02 γ-ray kerma, shown in the top panel of Fig. 6, is slightly reduced near the hypocenter, where the effect of the increased height of burst predominates. Beyond about 500 m, the other effects begin to predominate, and the kerma is increased by a factor approaching 10% at greater distances. In Hiroshima the neutron kerma of DS02 is lower than DS86 near the hypocenter, increases to values slightly more than 10% above DS86 at middling distances of the order of 1 km slant range, and falls off to values less than DS86 at distances beyond about 2 km, due to small differences in the neutron transport: changes in the neutron energy spectrum and new physical constants for scattering of neutrons by air.

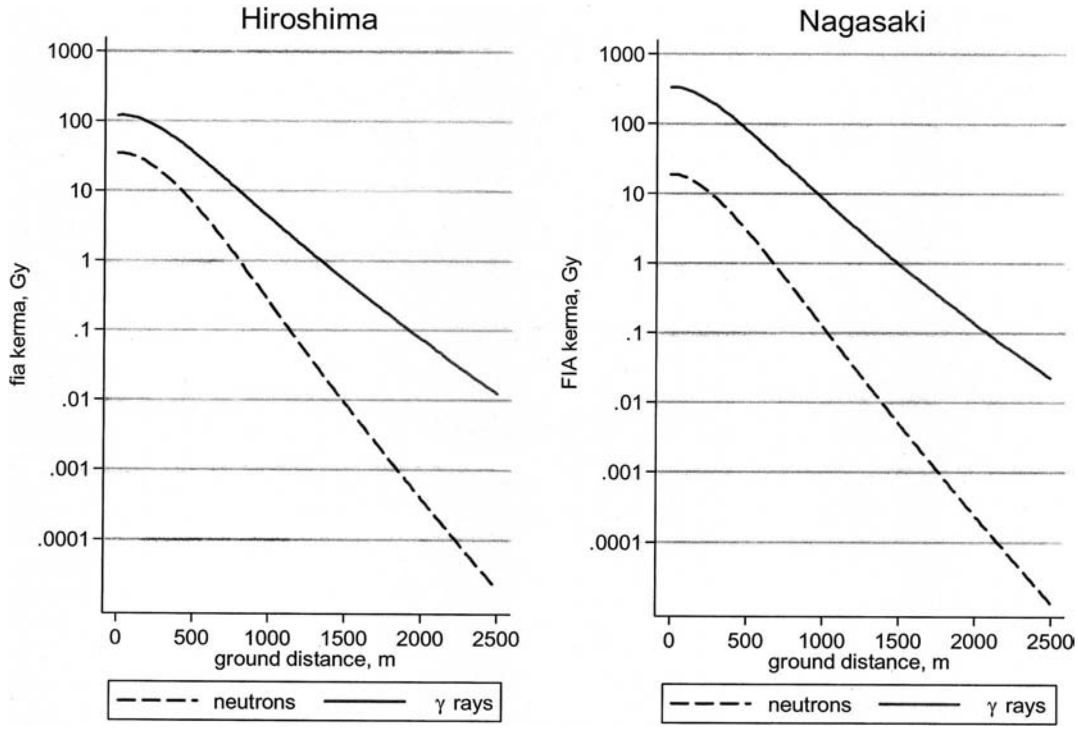

FIG. 5. DS02 free-in-air kerma values in Hiroshima and Nagasaki.

After careful consideration of the available evidence in Nagasaki, the working groups concluded that the yield and height of burst should remain unchanged. The predominant factor affecting Nagasaki γ-ray kerma is an increase in prompt γ rays per kiloton of yield. The magnitude of this change is similar to that for Hiroshima, and the reasons are similar, but the effect on dose estimates is larger for Nagasaki, since prompt γ rays account for a much higher proportion of the total γ-ray fluence in Nagasaki than in Hiroshima. The corresponding increase in γ-ray kerma is more uniform over distance, because the height of burst is unchanged. The most marked change of the new calcula-

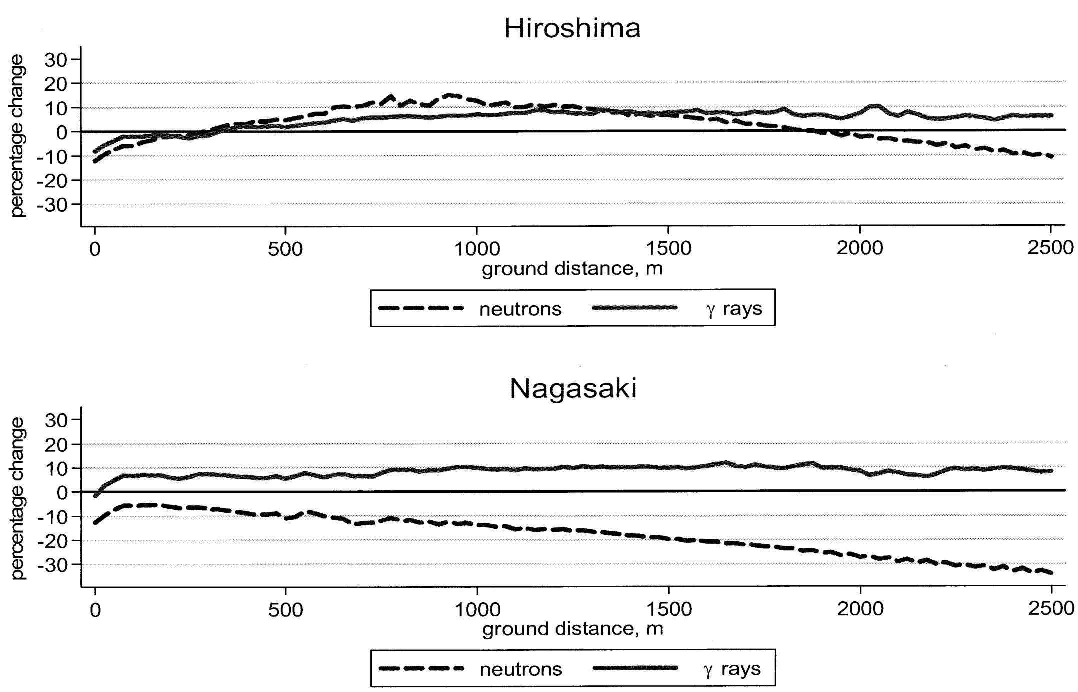

FIG. 6. Percentage change in free-in-air kerma from DS86 to DS02.

TABLE 3
Kerma-Weighted Mean Neutron and Gamma-Ray Energies (MeV) for DS86 and DS02 Free-in-Air Fluences

		Neutrons		Gamma rays	
City	Distance	DS86	DS02	DS86	DS02
Hiroshima	1000 m	1.15	0.96	2.87	2.81
	1500 m	1.60	1.33	3.33	3.26
Nagasaki	1000 m	1.66	1.47	2.81	2.84
	1500 m	1.98	1.71	3.38	3.36

tions is the overall reduction in neutron kerma in Nagasaki, which is due to similar effects related to neutron transport as just described for Hiroshima, but the corresponding effect on survivor doses is very small, because the neutron kerma comprises only a small fraction of the total kerma.

The transported total (prompt + delayed) free-in-air γ-ray fluence at survivor distances in DS02 changed very little in average energy from DS86. On the other hand, the transported free-in-air fluences of neutrons are less energetic in DS02, due primarily to new values of physical constants (''cross sections'') related to the interactions of neutrons with the nitrogen and oxygen in air. For example, at 1,500 m ground distance, the average neutron energy, weighted according to the contribution of each energy group to the total free-in-air tissue kerma, is about 17% less in DS02 than DS86 in Hiroshima and 14% less in Nagasaki. The values of mean energy given in Table 3 were calculated using this weighting with the 37 neutron energy groups and 21 γ-ray energy groups of DS86 and DS02 as

$$\bar{E} = \frac{\sum_{i=1}^{m} E_i N_i C_i}{\sum_{i=1}^{m} N_i C_i},$$

where E_i is the midpoint of the energy range covered by the ith energy group, N_i is the neutron or γ-ray fluence in the ith energy group, m is 37 for neutrons and 21 for γ rays, and C_i is the DS02 kerma coefficient for the ith energy group.

In addition to the changes in HOB and bomb yield in Hiroshima, DS02 defines minor changes in the locations of the hypocenters on the new city maps of both cities. These changes result from a refined alignment between the war-era U.S. Army maps used at RERF (*14*) and newer maps published by the governments of Hiroshima (1979) and Nagasaki (1981). However, both the survivor locations and the hypocenters defined previously in the frame of reference of the U.S. Army maps continue to be used in DS02. Therefore, as long as RERF continues to use the U.S. Army maps to define survivor distances, the distances will not change. Survivor distances may be affected individually by changes contemplated in the future, as information defining survivor locations is migrated to a system of the newer maps and war-era aerial photographs using a Geographical Information System (GIS). The nature and implications of these potential changes are discussed below in the section on Future Work.

In summary, the primary effect on total kerma and hence on survivor doses independent of shielding is an increase of 5 to 10% in both cities, due primarily to γ rays and thus basically illustrated by the γ-ray kerma values in the plots beyond 500 m ground distance and extending beyond 1,200 m, where most survivors are located.

5. Improvements in shielding calculations

The period between the initial implementation of DS86 and the development of DS02 allowed about 15 years of retrospective consideration. A number of improvements to DS86 shielding modules were made by outside consultants after the publication of the DS86 Final Report.[5,6] Based on RERF's experience over those years in implementing DS86, as well as their own separate analyses, developers of DS02 made a number of improvements, some of the more salient of which are discussed below. Since it is not feasible to show results of shielding modifications for both of neutrons and γ rays, the following sections are based solely on γ-ray kerma, which predominates for most organs and most survivors, even if weighting of the order of 20 to 50 is used for neutrons relative to γ rays. Qualitatively, the results of most of the DS02 shielding modifications are similar for neutrons and rays. More perspective on the relative size of neutron and γ-ray components is given below in the section on organ dose.

6. Frontal shielding of persons in houses and light structures

The nine-parameter classification of shielding provided by Japanese wooden houses, adopted from T65D models for use in DS86, includes a parameter for ''frontal shielding'' as defined above in the section on T65D. In DS86, a value of zero was assigned to all cases for which there was ''no shielding provided by a one-story house within seven or a two-story house within 6 to 12 m of the subject in the direction of the bomb.'' Seven meters and 12 m are twice the heights assumed for a one-story and two-story house, respectively.

Over the years after the development of DS86, it was determined that this ''rule of thumb'' could be improved upon, since adjacent structures in directions toward the bomb, even at distances greater than twice their height, do provide some frontal shielding for locations at longer distances from the hypocenter. For example, when shielding

[6] W. A. Woolson, M. L. Gritzner and S. D. Egbert, ''DS86: The Dosimetry System 1986 Software Description,'' provided to RERF by Science Applications International Corporation in 1989.

TABLE 4
Average Percentage Change in House Shielding Gamma-Ray Transmission Factors between DS86 and DS02 and Number of People Affected for all Persons in 9P Houses

Frontal shielding category		City: Hiroshima Percentage	Hiroshima People	Nagasaki Percentage	Nagasaki People	Total Percentage	Total People
Adjoining structure present[a]		+3	3,549	+3	712	+3	4,261
Adjacent structure present within one house height[a]		0	1,069	0	236	0	1,305
Adjacent structure present within two house heights[a]		−1	1,722	−1	423	−1	2,145
No adjacent structure present within two house heights[a]		(separate categories below)					
DS86	DS02						
No distinction regarding adjacent structures beyond 2 house heights	Structure present beyond 2 house heights in 1-o-s[b]	−12	3,507	−17	716	−13	(4,223)
	Structure present beyond 2 house heights, near but not in 1-o-s[b]	+1	1,022	+2	431	+1	(1,453)
	No structure present beyond 2 house heights near l-o-s[b]	+10	854	+12	1,019	+11	(1,873)
Total		−2	11,723	+1	3,537	−2	15,260

[a] Defined identically in DS86 and DS02.
[b] Line of sight to hypocenter.

was calculated by adjoint Monte Carlo for the locations in the house and tenement clusters used for DS86 model calculations that qualified as ''no frontal shielding'' under the above rule, the results indicated (e.g., a bimodal or multimodal frequency distribution) that there was a contribution to frontal shielding at distances beyond two house heights. The developers of DS02 subdivided all of the positions at various orientations in the model house cluster that were previously classified as having no frontal shielding into three categories based on the presence of structures beyond twice their own height within a sector 45° wide and centered on a ray to the hypocenter. DS02 shielding factors calculated for the model house and tenement clusters and sub-classified by this new designation could then be applied to survivor locations previously coded as ''no frontal shielding''. RERF staff recoded survivor records using specially developed interactive graphics software to indicate the sectors for each survivor on a scanned image of the neighborhood drawing from the relevant shielding history. The results in terms of percentage change from DS86 transmission factors are summarized in Table 4. For example, persons in 9P houses in Hiroshima who have no adjacent structure at any distance in the neighborhood drawing of their shielding history, within the 45° sector toward the hypocenter, have a DS02 transmission factor that is about 10% larger on average than they had in DS86. The distribution of individual changes was fairly wide, with substantial numbers of individuals having increases as large as about 20% and decreases as large as about −35%. The table also shows the number of survivors in various categories—a total of about 7,500 in both cities combined are affected by the change in coding of frontal shielding, i.e., those in the bottom three rows. The city difference in the frontal-shielding-category distributions largely reflects Hiroshima's higher housing density (e.g., houses per square kilometer)—for example, among survivor locations with no adjacent house within two house heights, locations in Hiroshima are more likely than locations in Nagasaki to have an adjacent house at some greater distance and less likely to have no house at all within a 45° sector toward the hypocenter.

It may also be noted that overall average γ-ray TFs changed very little in DS02 compared to DS86, in contrast to the difference between T65D and DS86, consistent with the slight change in the energy distribution of the total transported free-in-air fluence, as noted above in the section on changes in bomb parameters and overall changes in free-in-air kerma under DS02 (Table 3).

7. Persons in schools and other large wooden buildings

The house cluster models developed for DS86 did not include larger wooden buildings such as schools, but the 9P model was applied to such buildings. The implications of this were realized when a small study was performed for DS02 in which biodosimetric measurements (electron spin resonance measurements of γ-ray dose using tooth enamel, and chromosome aberration measurements) for 41 subjects were compared to their calculated doses. Because survivors in such buildings seemed to have a poorer correlation of biodosimetry to calculated doses, a new detailed model calculation was performed for the Hirose Elementary School. This confirmed that such large wooden buildings have larger γ-ray transmission factors than would be supposed based on the application of the nine-parameter data and the DS86 house model, because they have larger rooms and fewer interior walls than houses, for a given ‘‘slant penetration’’ distance (defined above in the section on T57D). In Hiroshima, 639 survivors in schools were affected with a mean change of +31% in transmission factor, whereas in Nagasaki only 67 were affected but had the same mean change of +31%.

8. Globe model for shielding of persons outside but shielded by nearby houses

For the method based on the earlier ‘‘globe’’ model for calculating the shielding that survivors *outside* of buildings receive from nearby buildings, DS86 uses only a single leakage file from positions located outdoors in the house and tenement model clusters—the one whose unblocked proportion of neutron fluence is closest to that of the survivor being calculated. DS02 seeks to minimize the variability of this scheme by using an average of the six positions with unblocked proportions of neutron fluence closest to that of the survivor’s globe data. Many of the individual changes are substantial but the average effect is slight: The standard deviation of percentage change in transmission factor was about 15% in Hiroshima and 19% in Nagasaki, whereas the average percentage change was about + 1% in Hiroshima (2,924 survivors) and + 2% in Nagasaki (593 survivors). This variation in changes among individuals is not the same as the variation that the new method is intended to reduce. The latter could be evaluated only by doing a series of custom Monte Carlo calculations for a set of survivor locations, to produce a sort of ‘‘gold standard’’ set of TFs for comparison. Then the intention of the new method is that for that set of cases, var(new TF/custom TF) should be <var(old TF/custom TF), whereas the variance in the percentage change noted above is proportional to var(new TF/old TF).

9. New factory models

In the 1988 supplement to DS86 the factories were modeled as shells, with no consideration given to shielding by interior features. In the years after the publication of DS86 it became increasingly apparent that Nagasaki factory workers had fewer chromosomal aberrations overall than other survivors with similar calculated doses in wooden houses and other shielding situations (*63*).

In the preparation of DS02, a scoping study using a two-dimensional discrete ordinates calculation suggested that such common interior features as workbenches, hand tools and some machine tools would provide considerable shielding that had not been included in the 1988 model.[5] Investigators therefore performed a detailed Monte Carlo Adjoint Shielding Code (MASH) calculation to determine the shielded fluences for 40 representative worker locations in the largest factory building: the final torpedo assembly building of the Ohashi Plant of the Mitsubishi Ordnance Factory. This suggested that a worker’s position relative to workbenches made a difference in transmission factor if it was assumed that the workers were knocked down by the blast or ducked for cover and therefore were no longer in a standing/sitting position thereafter, since a portion of the dose at the relevant distances is attributable to delayed radiation after the arrival of the blast wave. However, a detailed analysis implementing new leakage files based on these calculations revealed that dose reductions due to being prone after the blast were generally not very large, since a relatively small portion total kerma is received after the arrival of the blast wave. For example, the blast wave arrives about 2.5 to 3 s after the detonation at distances of 1300 to 1400 m, after all of prompt and about half (neutrons) to three-fourths (γ rays) of the delayed radiation has been received. The DS02 modification allows RERF some discretion in the timing to be used in actual implementation, which could consider further studies regarding the reaction time involved, whether workers might have started to take cover earlier than blast wave arrival due to the flash, etc.

Another aspect of the new calculation was that workers near exterior building walls, particularly in the direction of the bomb, had higher doses than others due to radiation streaming in through windows and doors. Of the 650 workers with complete shielding information in buildings suitable for this type of factory model, only 97 who were distant (>30 m) from the exterior wall toward the bomb and within 2 m behind benches had a change in transmission factor exceeding 1%, and under the present assumption of changing from standing to prone at the exact blast wave arrival time, their average reduction was only about 8%. RERF plans further evaluation of other factors such as checking factory distance with the Geographical Information System (GIS), which has different implications for factory workers than other survivors because many workers’ distances are all determined by the estimated location of a single building. RERF may also evaluate the feasibility of obtaining additional calculations related to matters such as partial body shielding by benches, etc., and indications in some factory drawing of objects not included in the DS02 model that may have provided shielding. The latter would need to be evaluated as to whether there is a quantitative basis for adding particular types, amounts and locations of such shielding to the model.

10. Distal terrain (‘‘mountain’’) shielding

The 1988 Nagasaki proximal terrain-shielding model[5] has been documented as part of the DS02 report and will continue to be used. It provides a full set of shielded fluences and can be used in conjunction with the nine-parameter model for survivors in houses or with a model based on a template that was developed for the 1988 model to define shielding by nearby buildings for survivors outdoors.

Both the DS86 and 1988 models were envisioned for use

TABLE 5
Average Percentage Change in Transmission Factors[a] for All Persons Coded as being Affected by Distal Terrain (Mountain Shielding)[b]

	City					
	Hiroshima		Nagasaki		Total	
DS02 shielding category	Percentage change	People	Percentage change	People	Percentage change	People
Average house	−11	1,903	−41	3,456	−30	5,359
Average outside	+4	753	−33	1,352	−20	2,105
Total	−6	2,675	−38	4,899	−27	7,574

[a] Defined as shielded kerma/free-in-air kerma.
[b] Data not shown for one survivor coded ''In Open,'' 95 survivors with 9P house data, and 13 survivors with globe data, due to the small number of survivors in these categories that are affected by mountain shielding.

with relatively small hills, at ground distances within 2.5 km, where DS86 fluences and hence directly calculated doses were available. The terrain shielding of survivors at longer distances was considered at the time to be of limited interest due to the small doses involved; the DS86 free-in-air γ-ray kerma at 2.5 km is about 12 mGy in Hiroshima and 21 mGy in Nagasaki, and the neutron kerma is well under 1% of these values. In the interim, more scientific interest has been focused on acute doses in this range, and it has been recognized that two large hills, Hijiyama in Hiroshima (~50 m high at ~1,900 m ground range) and Konpirasan in Nagasaki (~280 m high at ~1,600 m ground range), provided shielding for large numbers of survivors at distances between about 2 km and 3 km.

Based on a detailed calculation performed for Hijiyama, investigators recommended that, although the 1988 model was intended for smaller terrain features, it provides acceptably accurate estimates for use with the distant large hills and mountains in the two cities. This affects relatively few survivors in Hiroshima because Hijiyama has a rather small shadow, but it affects a considerably larger number in Nagasaki, as shown in Table 5. The changes shown in this table are for a combined transmission factor that incorporates the effect of any shielding due to houses, etc., in addition to the distal terrain feature (''mountain'')—the vast majority of survivors affected by distal terrain are also in categories for which there is other assumed shielding that is calculated using either an averaged value for survivors in houses or for those out of doors. In Hiroshima, most survivors affected by Hijiyama received comparatively little shielding because of its small size, and the more pronounced difference from DS86 is the explicit consideration in DS02 of whether they were indoors or outdoors. In the implementation of DS86, survivors at longer distances, including almost all of those who are now considered to be affected by mountain shielding, were assigned an overall average transmission factor like that of the ''average any'' group of DS02, as defined below in the section on average transmission factors, i.e., an average over all persons with coded shielding information, both indoors and outdoors, which therefore included some fraction of house shielding. Those who are now given an ''average outside'' TF therefore show a slight increase overall, despite the fact that some of them receive some mountain shielding.

Organ Dose

DS02 organ doses are calculated using the same methods as DS86, although the RERF implementation of DS02 uses age-specific average ''transmission factors'' for the body's self-shielding in calculating indirect doses, whereas the implementation of DS86 used averages taken for all ages. The developers of DS02 defined new fluence-to-organ-dose conversion factors using the latest values of physical constants and a re-evaluated formulation, but the resulting values do not differ much from those used in DS86. However, there *is* a difference between DS86 and DS02 in the attenuation of neutrons due to shielding. The DS02 free-in-air neutron fluences at survivor distances have a different energy distribution and are somewhat more easily attenuated than the DS86 free-in-air neutron fluences in both cities. Because neutrons are attenuated to a greater degree than γ rays by the type of shielding present in light wooden structures, and particularly by the body's own self-shielding, due to the body's high hydrogen content, the neutron kerma is smaller relative to the γ-ray kerma for shielded kerma than for free-in-air kerma and even smaller for internal tissues and organs, as shown in Fig. 7. This is more pronounced in DS02 than in DS86. As shown in Fig. 8, the percentage change in neutron colon dose from DS86 to DS02 is lower than the percentage change in γ-ray colon dose, because the γ-ray energy distribution did not change as much as that for the neutrons and was lower than the percentage change in either neutron or γ-ray free-in-air kerma (Fig. 5) because of the reduced overall neutron TFs for house and body shielding. Figures 7 and 8 are based on grouped data for individual survivors on 50-m intervals of ground dis-

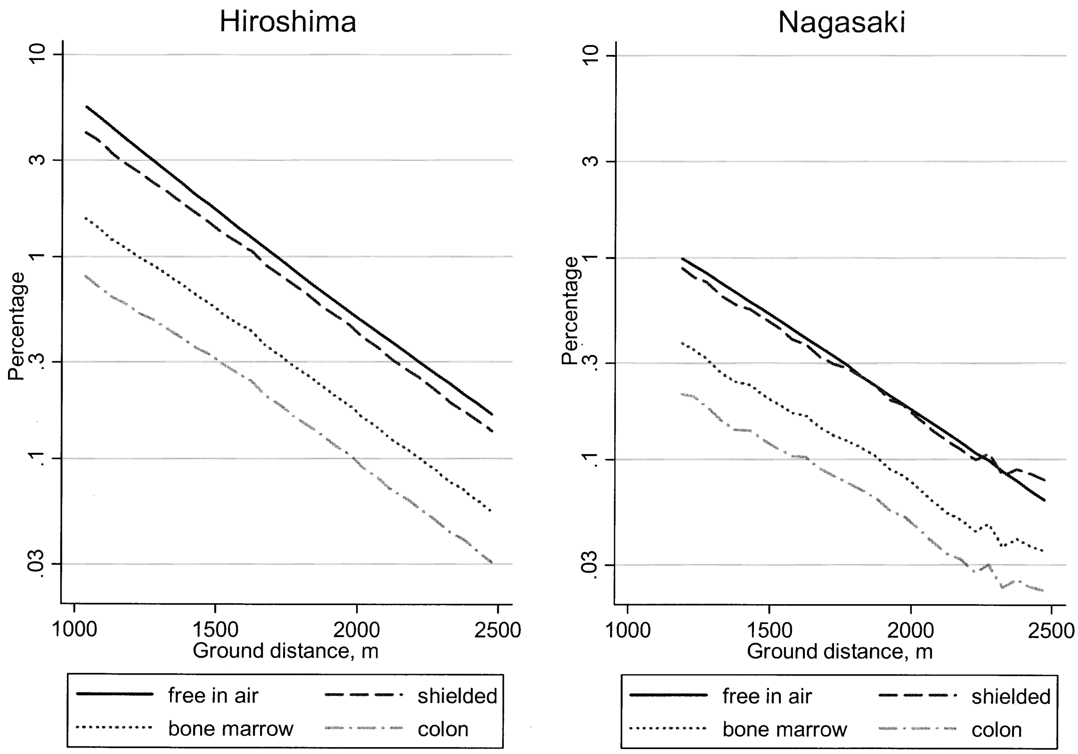

FIG. 7. Neutron kerma (dose) as percentage of γ-ray kerma (dose) for successive levels of shielding and self-shielding (grouped data on 50-m intervals).

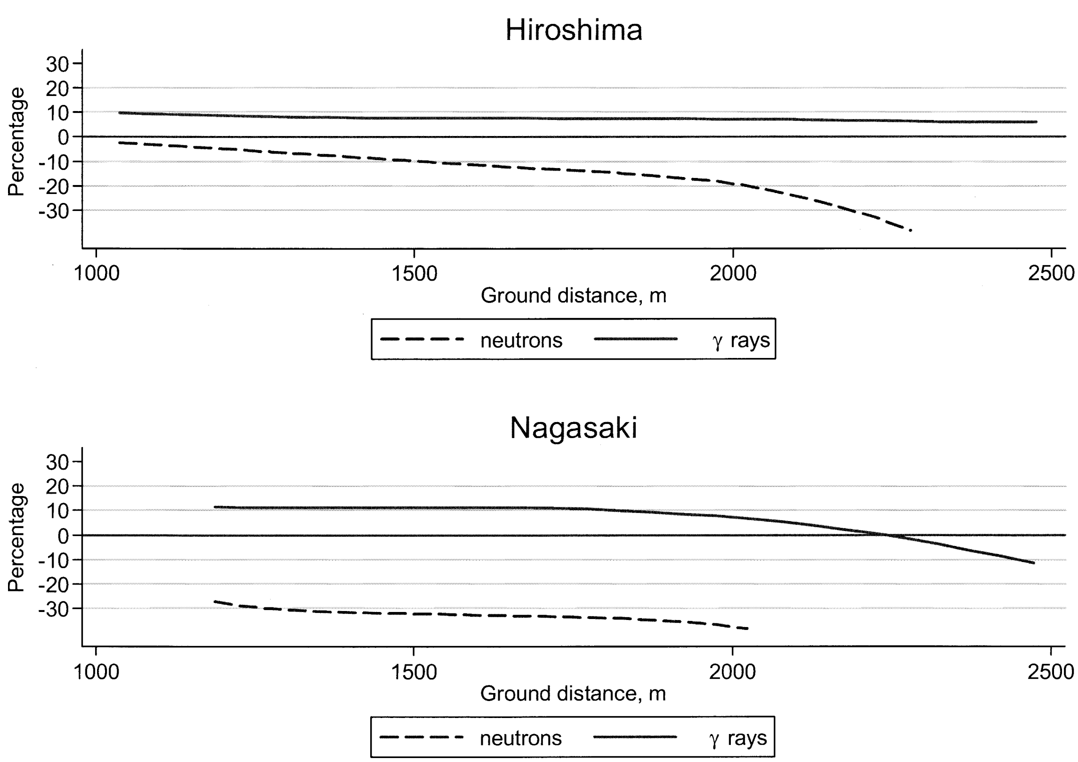

FIG. 8. Percentage change in colon dose from DS86 to DS02 (lowess smooth of grouped data on 50-m intervals).

tance from the distance where the unweighted sum of neutron + γ-ray free-in-air kerma = 4 Gy.

The other effect on the percentage change in colon dose from DS86 to DS02 that is not seen in free-in-air kerma (Fig. 8 compared to Fig. 5) is a reduction at greater distances in Nagasaki for both neutrons and γ rays due to the shielding provided by the large hill Konpirasan for a large portion of survivors at those distances.

RERF Implementation

The core DS02 and DS86 systems installed at RERF consist of computer programs and databases that can be used to compute estimates for survivors with complete shielding histories who were within 2,500 m of the hypocenter at the time of the bombings. The systems provide estimates of free-in-air tissue kerma, tissue kerma adjusted for the effects of shielding by Japanese-style houses or tenements, and absorbed dose for 15 organs. Although DS02, like DS86, is a fairly complete dose calculation system, considerable implementation work is required at RERF. Some of this work is purely administrative, such as assembling the necessary data for designated survivors and maintaining current versions of the DS86/DS02 codes and databases that can be run on up-to-date hardware and software platforms. Other work, however, involves more scientific decision-making that can be classified into three categories for the purposes of this discussion:

1. Determining appropriate rosters of survivors for the calculation of doses as described earlier in this paper.
2. Devising methods to calculate doses for survivors of interest whose dose cannot be calculated directly by DS02 methods.
3. Determining appropriate *post hoc* adjustments to calculated doses for use in epidemiological studies, to correct for known causes of statistical bias or other problems.

1. Indirect dose calculations

As noted above, the direct calculation of dose is possible only out to a distance of 2.5 km, the range of the tabulated fluences included in the DS86 and DS02 database files. Beyond this distance, doses must be imputed by indirect methods not included in the core DS86/DS02 system.

The first step in addressing the 2,500-m dose computation limit was the development of city-specific regression estimates for each of the four free-in-air-kerma components (prompt and delayed neutrons and γ rays) that can be used to provide *kerma* estimates at any distance of interest.

Dose estimation for distant survivors is also complicated by the fact that almost none of the survivors beyond 2.5 km have shielding information, and there are some survivors at closer distances for whom some shielding information is available but who lack the full complement of detail necessary for Globe or nine-parameter calculations. Doses for all such survivors are calculated using a separate method to calculate averaged transmission factors, which are then applied to the free-in-air kerma values from the regression for the particular distance.

2. Regression estimates of free-in-air kerma components

Regression estimates for both DS86 and DS02 are based on the set of kerma component estimates provided by the system at 25-m intervals from 700 m to 2,500 m. RERF began in the implementation of DS86 by considering linear regression models of the form

$$\ln(K) = \alpha + \beta r - 2\ln(r), \tag{2}$$

where K is one of the four free-in-air kerma components and r is the slant range. This is a different expression for the form used in T65D (Eq. 1), in which K_0 corresponds to $\exp(\alpha)$ and the relaxation length is equal to $-1/\beta$. Although this simple model provided a reasonably good fit, it was found that estimating an additional parameter, γ, related to the change in kerma with $\ln(r)$ significantly improved the fits, and this method was used for DS02. This extended model can be written as

$$\ln(K) = \alpha + \beta r_{\gamma} - 2_{\gamma}\ln(r)$$

or, equivalently,

$$K = \frac{K_0 \exp(\beta r + \gamma \ln(r))}{r^2}.$$

This can be interpreted as a model with a distance-dependent relaxation length given by the derivative of the exponent with respect to the slant range; i.e.

$$\rho(r) = \frac{1}{\beta + (\gamma/r)} = \frac{r}{\beta r + \gamma}.$$

The models were further extended by allowing linear splines in r and $\ln(r)$ with knots at 1000 m and 2000 m. The final DS02 model can be written as

$$\ln(K) = \begin{cases} \alpha_1 + \beta_1 r + (\gamma_1 - 2)\ln(r) & \text{if } r \leq 1000; \\ \alpha_2 + \beta_2 r + (\gamma_2 - 2)\ln(r) & \text{if } r \leq 1000; \\ \alpha_3 + \beta_3 r + (\gamma_3 - 2)\ln(r) & \text{if } r \leq 1000; \end{cases}$$

where the parameters are constrained to ensure that the functions on adjoining intervals are equal at the 1000-m and 2000-m join points. (The DS86 free-in-air kerma regression models have only a single join point at 1000 m.) Functions of this form provide excellent fits to the free-in-air fluence components over the entire range from 0 to 2500 m. Figure 9 presents the percentage differences between the DS02 free-in-air total γ-ray and total neutron kerma estimates and the free-in-air kerma regression estimates by ground distance for each city, which are too small to be distinguishable on a semi-logarithmic plot of the direct and indirect estimates as a function of distance. The observed

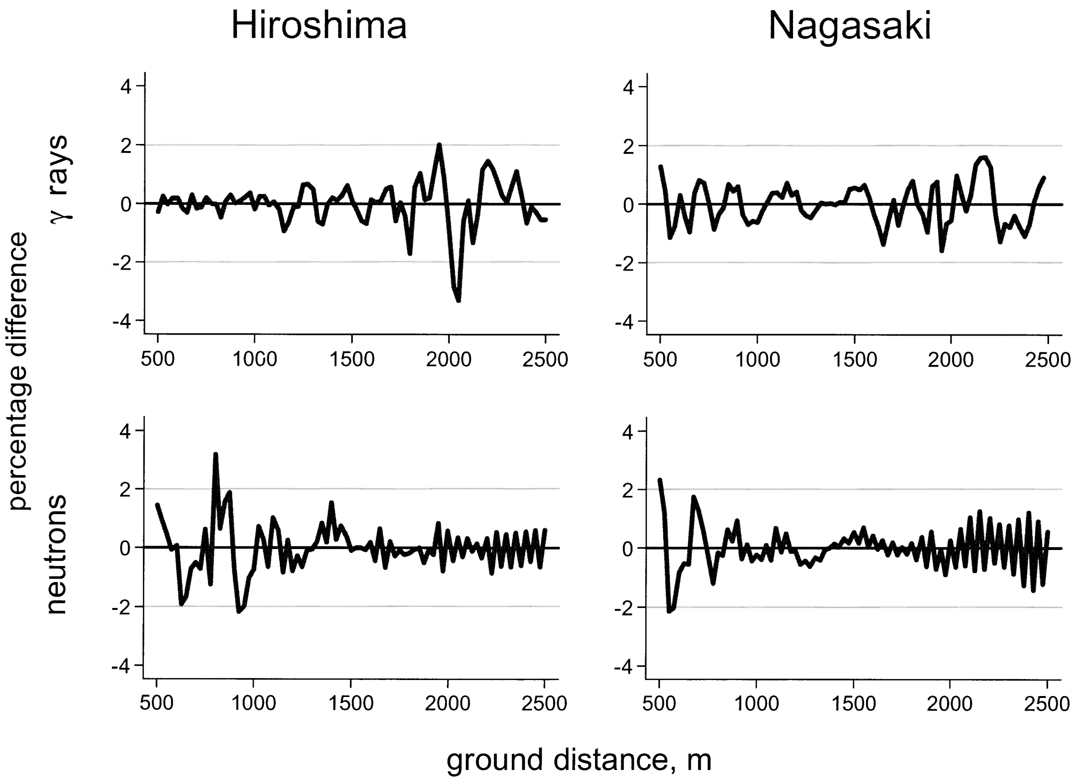

FIG. 9. Percentage difference between indirect free-in-air kerma and DS02 direct estimates.

difference between the regression estimates and DS02 direct estimates is typically less than 2% at both cities and is due to small fluctuations in the DS02 direct estimates arising from the discrete nature of the spatial grid and the energy groupings in the discrete ordinates transport calculations. The splines, in contrast, are smooth functions with gradual curvature that join smoothly but change slope and curvature (i.e., on a semi-logarithmic plot) by a small amount at the join points. We feel that the indirect estimates are slightly better values at all distances than one gets by simply interpolating the DS02 direct estimates between grid points, because they are very good fits overall, and the physics suggests that the true change in kerma with distance has a slope (on a semi-logarithmic plot) that changes gradually as the energy spectrum of the fluence changes due to differential attenuation at different energies. The DS86 free-in-air regression model parameter estimates are available on the RERF website at www.rerf.jp, and the DS02 estimates are given in the Appendix and will be made available on the RERF website.

3. Average transmission factors

Average transmission factors were used to compute shielded kerma and organ dose estimates for survivors beyond 2,500 m and some proximal survivors with partial shielding information (primarily people who were known to have been exposed in or near houses for whom nine-parameter data are not available). These average transmission factors were computed from the empirical transmission factors for cohort members for whom direct estimates are available.

Three sets of city-specific average transmission factors are used in shielded kerma computations. Each set consists of values for the six shielded kerma components: prompt and delayed neutrons and γ rays transported from the bomb and γ rays generated by prompt and delayed neutron interactions with the shielding materials. The average shielded kerma transmission factor groups are:

Average house	People exposed in houses or other light structures with nine-parameter data
Average outside	People who were outside with structure or terrain shielding
Average any	Population average

The averages for the first two groups were computed using direct estimates for all relevant survivors with direct DS02 estimates. The values used for the third group were computed as a weighted average of the first two groups with weights reflecting the relative proportion of survivors in the two groups. The DS02 average transmission shielded-kerma factors for these three groups will be made available through the RERF website and are given in the Appendix.

Indirect organ dose estimates were computed by applying average organ transmission factors to the shielded kerma components. Average organ-dose component transmission factors for the eight organ-dose components were computed from the empirical organ dose component estimates for people with direct DS02/DS86 estimates. The organ dose components include the six shielded kerma components together with two additional components for γ-ray doses that arise from the interaction of prompt and delayed neutrons with tissues in the body. In DS02, as in DS86, average organ dose transmission factors vary with organ, city, and age at exposure in three groups: ''infants'' (0–2 years old), ''children'' (3–11 years old), and ''adults'' (12 or more years old). Average transmission factors were computed for each of the 15 organs considered in DS02 and DS86, while maximum skin doses are assumed to be equal to the shielded kerma. The averages were computed without regard to the nature of the external shielding. Representative values (colon and bone marrow) are given in the Appendix, and the full set will be made available on the RERF website.

4. Calculation methods

To facilitate the computation of DS02 dose estimates, survivors were jointly classified into 14 shielding categories and five calculation groups. The shielding category definitions are:

In Open — outside with no reported shielding and having suffered flash burns

9P House — inside a house or similar light structure with detailed shielding (nine-parameter) data

9P School — inside a large wooden structure with nine-parameter data

9P Fact — inside a light factory building, nine-parameter data

9P Other — inside other types of buildings with nine-parameter data

Naga Fact — inside a Nagasaki factory building, includes both modeled and unmodeled factories

Globe — outside shielded by nearby houses with ''globe'' modeling data

Globe Terrain — outside shielded by terrain features and houses with ''globe'' modeling data

Average House — inside a house or other light structures without nine-parameter data

Concrete — inside a concrete building

Other Outside — outside with other shielding including proximal survivors who reported no external shielding but did not report flash burns

Other Any — approximate location known but not known whether inside or outside

NIC — not in the city at the time of the bomb

No Info — no shielding information

The calculation groups and short names are:

Proximal/Surveyed — within 1,600 m of the Hiroshima hypocenter or 2,000 m of the Nagasaki hypocenter at the time of the bombs. These are the ground ranges within which there was a systematic effort to obtain detailed shielding histories. The free-in-air kerma estimates for this group are in excess of 355 mGy in Hiroshima and 135 mGy in Nagasaki in the absence of mountain shielding.

free-in-air >10 mGy — distant (i.e., not in the proximal ranges where shielding histories were systematically collected) survivors with unweighted total (neutron + γ-ray) free-in-air kerma of at least 10 mGy. (In the absence of mountain shielding, this corresponds to distances less than 2,565 m in Hiroshima and 2,765 m and Nagasaki.)

free-in-air 0.5 mGy — survivors with unweighted total (neutron + γ-ray) free-in-air kerma at least 0.5 mGy and less than 10 mGy. (In the absence of mountain shielding, this corresponds to distances between 2,565 and 3,480 m in Hiroshima and between 2,765 and 3,855 m in Nagasaki.)

free-in-air <0.5 mGy — survivors with unweighted total (neutron + γ-ray) free-in-air kerma less than 0.5 mGy. Members of the NIC shielding category are included in this group. DS02 kerma and dose estimates for people in this group were set to 0.

Location unk — Location at the time of the bomb unknown but likely to have been within 10 km of the hypocenter. DS02 kerma and dose estimates for people in this group were treated as unknown.

The basic DS02 system was used to compute direct estimates of free-in-air kerma for all survivors within 2,500 m of the hypocenters, while the DS02 free-in-air kerma regression estimates were used for people exposed at greater distances. The basic DS02 system can directly compute shielded kerma and organ dose estimates for many of the shielding categories. For survivors in these categories who were beyond 2,500 m from the hypocenter, computations were made by initially treating them as if they were exposed at 2,500 m, deriving individual empirical transmission factors for the various shielded kerma and organ dose

TABLE 6
DS02 Shielded Kerma Computation Methods by Shielding Categories and Calculation Groups[a]

DS02 Shielding category	DS02 calculation group				
		Distant			
	Proximal/ surveyed	Free-in-air >10 mGy	Free-in-air >0.5 mGy	Free-in-air <0.5 mGy	Location unknown
In open[b]	Direct[c]	Direct			
9P house	Direct	Direct	Direct	Assigned 0	
Average house	Average house	Average house	Average house	Assigned 0	Unknown
9P school	Direct	Direct	Direct	Assigned 0	
9P factory	Direct	Direct		Assigned 0	
Factory[d]	Direct	Direct		Assigned 0	
9P other	Direct	Direct		Assigned 0	
Globe	Direct	Direct			
Globe terrain	Direct	Direct			
Concrete	Unknown	Unknown			
Other outside	Unknown	Average outside	Average any	Assigned 0	
Other Any	Unknown	Unknown		Assigned 0	
NIC				Assigned 0	
No info	Unknown	Unknown	Average any	Assigned 0	Unknown

[a] Shielding category and calculation group definitions are given in the text. Shaded cells in this table contain no people.
[b] Limited to people reporting flash burns.
[c] Computed directly by the basic DS02 system.
[d] DS02 computations could only be carried out for Nagasaki survivors in modeled factories.

components and then applying these factors to the free-in-air kerma regression estimates at the survivor's reported distance. The average transmission factors described above were used for people in a number of other shielding categories, while doses were treated as unknown for people in some categories who were relatively close to the hypocenter. Table 6 summarizes the methods used to compute shielded kerma in the various combinations of shielding categories and calculation groups.

Table 7 summarizes the distribution of people in the full DS02 roster (which includes LSS cohort members, mothers of people exposed *in utero*, and parents of people included in various RERF F1 studies) by shielding category and calculation group for each city. Table 8 presents the same information for the LSS specifically.

The final step in the RERF implementation of DS02 was to replace direct kerma and dose estimates by indirect estimates for people who were within 2,500 m of the hypocenters, for the reasons discussed above under *Regression estimates of free-in-air kerma components.* As indicated by the results shown in Fig. 9, this change has no appreciable impact on individual dose estimates, but it does serve to eliminate some very small artifacts in the direct estimates that arise from the discrete nature of the DS02 transport computations.

The first step in this process was to compute individual empirical shielded kerma and organ dose transmission factors from the direct estimates. The resulting shielded kerma transmission factors were applied to indirect free-in-air kerma regression component estimates to produce indirect shielded kerma component estimates, which were then converted to organ dose estimates by application of the individual's organ dose transmission factors.

5. *Adjustments for the effect of dose error*

Uncertainties in survivor dose estimates arise for various reasons. Knowledge of the nature of the radiation released by the bomb, its transport through the air, and the effect of shielding is limited and, as the above discussions have made clear, the survivor dosimetry system involves a number of reasonable assumptions and approximations regarding all of these factors. Furthermore, information on location and shielding is incomplete and imprecise for individual survivors of interest to RERF. There are several reports on the magnitude of random errors in the dose estimates

TABLE 7a
DS02 Dose Computation Summary: Hiroshima DS02 Roster

DS02 shielding category	DS02 calculation group							Total		
			Distant							
	Proximal/surveyed		Free-in-air >10 mGy		Free-in-air >0.5 mGy	Free-in-air <0.5 mGy	Location unknown			
	Known	Unknown	Known	Unknown	Known	Known		Known	Unknown	Total
In open[a]	912		8					920		920
9P house	8,735		3,818		42	9		12,604		12,604
Average house	3,059		16,336		8,245	12,527	14	40,167	14	40,181
9P school	469		242		4	6		721		721
9P factory	277		81		7	1		366		366
Factory		11		14		1		1	25	26
9P other	154		72			1		227		227
Globe	2,000	2	1,121					3,121	2	3,123
Globe terrain										
Concrete		297							297	297
Other outside		368	7,789		3,753	6,735		18,277	368	18,645
Other any		2,129		1,276					3,405	3,405
NIC						64,094		64,094		64,094
No information		147		1,289	940	2,122	6,070	3,062	7,506	10,568
Total	15,606	2,954	29,467	1,290	12,991	85,496	6,084	143,560	10,328	155,177

[a] Limited to people reporting flash burns.

and the effect of these errors on risk estimation (*64*, *65*) in the T65D system. However, it was not until shortly after the introduction of DS86 that there was a practical system that could be applied easily for routine analyses. This system, described in detail in ref. (*66*), makes use of information on the nature of the uncertainties in the dose estimates for individual survivors and the distribution of ''true'' doses in the population to derive city-specific adjustments that are used to compute an expected true dose for each survivor. These adjustment factors are functions of the estimated shielded kerma. The error-adjusted individual dose estimates are called the *survivor dose estimates* to distinguish them from the unadjusted dose estimates.

The adjustments that have been used in most analyses have assumed 35% random errors in individual survivor dose estimates and a highly skewed (toward low doses)

TABLE 7b
DS02 Dose Computation Summary: Nagasaki DS02 Roster

DS02 shielding category	DS02 calculation group							Total		
			Distant							
	Proximal/surveyed		Free-in-air >10 mGy		Free-in-air >0.5 mGy	Free-in-air <0.5 mGy	Location unknown			
	Known	Unknown	Known	Unknown	Known	Known		Known	Unknown	Total
In open[a]	368		1					369		369
9P house	3,315		281		2			3,598		3,598
Average house	721		6,558		7,073	7,036	18	21,388	18	21,406
9P school	67							67		67
9P factory	233		5					238		238
Factory	813	223	1	3				813	225	1,039
9P other	104		2					106		106
Globe	575		36					611		611
Globe terrain	350	8	4	1	1	8		363	9	372
Concrete		494							494	494
Other outside		391	2,588		2,470	2,908		7,966	391	8,357
Other any		2,015		1,082					3,097	3,097
NIC						42,608		42,608		42,608
No information		103		418	4,384	6,030	5,143	10,414	5,246	16,078
Total	6,546	3,234	9,476	1,503	13,930	58,590	5,161	88,541	8,398	98,440

[a] Limited to people reporting flash burns.

TABLE 8
LSS DS02 Dose Computation Summary

DS02 shielding category	DS02 calculation group						Total		
			Distant						
	Proximal/surveyed		Free-in-air >10 mGy		Free-in-air >0.5 mGy	Free-in-air <0.5 mGy			
	Known	Unknown	Known	Unknown	Known	Known	Known	Unknown	Total
Hiroshima									
In open[a]	838		8				846	0	846
9P house	6,782		3,253		19	3	10,057	0	10,057
Average house	2,062		14,509		5,370	7,324	29,265	0	29,265
9P school	401		225		3	3	632	0	632
9P factory	241		79		3		323	0	323
Factory		11		14			0	25	25
9P other	127		69			1	197	0	197
Globe	1,611	1	999				2,610	1	2,611
Globe terrain									
Concrete		218					0	218	218
Other outside		119	7,062		2,599	4,116	13,777	119	13,896
Other any		1,772		1,142			0	2,914	2,914
NIC						20,230	20,230	0	20,230
No information				172	325	503	828	172	1,000
Hiroshima total	12,062	2,121	26,204	1,328	8,319	32,180	78,765	3,449	82,214
Nagasaki									
In open[a]	292		1				293	0	293
9P house	2,560		241				2,801	0	2,801
Average house	450		6,379		5,168	3,582	15,579	0	15,579
9P school	56						56	0	56
9P factory	183		4				187	0	187
Factory	652	179		1			652	180	832
9P other	75		1				76	0	76
Globe	461		33				494	0	494
Globe terrain	303	7	4			1	308	7	315
Concrete		478					0	478	478
Other outside		296	2,526		1,887	1,729	6,142	296	6,438
Other any		1,572		1,062			0	2,634	2,634
NIC						6,350	6,350	0	6,350
No information				26	926	622	1,548	26	1,574
Nagasaki total	5,032	2,532	9,189	1,089	7,981	12,284	34,486	3,621	38,107
Both cities	17,094	4,653	35,393	2,417	16,300	44,464	113,251	7,070	120,321

[a] Limited to people reporting flash burns.

distribution of true doses for survivors. The choice of 35% errors was based largely on the information in refs. (*64*, *65*). At the time of the development of the DS86 dose-error adjustments, various biological end points were used to provide information on the likely magnitude of the uncertainty in individual doses (*67*, *68*). These analyses also supported the assumption of 35 to 40% errors in individual dose estimates. Allowance for errors of this magnitude typically increases risk estimates by 10–15%.

LSS Report 12 (*69*) was the first major report to make use of DS86 survivor dose estimates. Since that time survivor dose estimates have been used for most analyses of RERF mortality and incidence data. Figure 10 presents the dose-adjustment factors as a function of shielded kerma by city. At present, DS02 uses the same dose-error adjustments as DS86. However, as noted in the following discussion of future work, some changes may eventually be made in the methods used to compute the dose-error adjustment factors.

MANAGEMENT AND USE OF RERF DOSIMETRY DATA

The DS02 dosimetry system makes use of a broad range of information from a number of disparate sources. The system provides up to 260 kerma and dose component estimates for each person with non-zero dose estimates. A well-designed database is essential for effective management and use of these data. Over the past several years RERF researchers have worked closely with database experts to design and implement a comprehensive and accessible dosimetry database within the larger RERF research database.

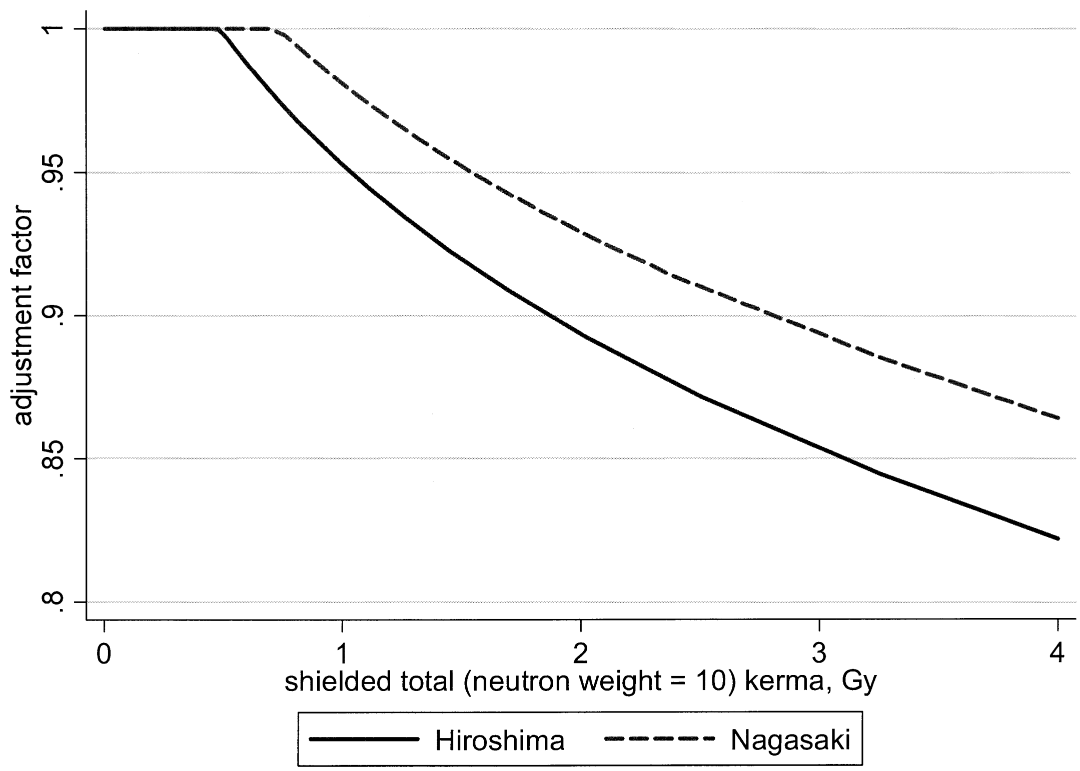

FIG. 10. Factors used to adjust survivor doses for dose error as a function of shielded kerma.

The DS02 roster, which identifies all individuals whose exposure status and dose are relevant to RERF studies, provides the link between basic information, such as gender, age at exposure, and follow-up data, and dosimetry related data, such as location and shielding data (including shielding history images) and the actual dose component estimates. The database also includes summary tables that provide total γ-ray and total neutron dose estimates, which is a level of detail more appropriate for most uses than component-specific estimates. The primary summary tables contain the DS02 survivor dose estimates (i.e., estimates that incorporate the standard adjustment to reduce bias in risk estimates that arises from random errors in individual dose estimates). The total γ-ray and total neutron estimates in these tables are stored with three-digit precision.

While users at RERF have access to virtually all of the detailed dosimetric data, the primary method for obtaining dose estimates makes use of a simple but powerful database access application that allows the user to link the relevant dose information with demographic and follow-up data for the study group and produce output datasets for analyses with a few clicks of the mouse (*70*).

THE EVOLUTION OF RERF DOSE ESTIMATES: AN EXAMPLE

Tables 9 and 10 show an example chosen to illustrate several aspects of the changes in dosimetry through the various systems, using a hypothetical survivor with typical attributes (i.e., an adult in a standing position, facing toward the bomb, in a typical house). In addition to the changes in dose, the increasing detail and specificity of the dose estimates are evident. The differences in calculated dose reduction due to shielding are also shown implicitly; i.e., they can be calculated readily by taking the values given and calculating ratios of shielded kerma to free-in-air kerma, colon dose to shielded kerma, etc. It should be noted that the reduction in the γ-ray transmission factor of the house shielding between DS86 and DS02, from 244 mGy/488 mGy = 0.5 to 225 mGy/525 mGy = 0.43, is due to the consideration of additional frontal shielding more than two house heights' distant in the DS02 recoding of the shielding parameter ''FS'', rather than being due to the energy spectrum of the incident free-in-air fluences. The γ-ray energy spectrum changed very little, as discussed above in the section on *Frontal shielding of persons in houses and light structures.*

CONCLUSION AND FUTURE WORK

A clear intention of the dosimetry reassessment that led to DS02 has been that it should be a ''final'' system (*58*) and should not leave unresolved issues that would lead to the sort of misgivings that characterized its predecessors. The agreement between measured and calculated values and the thorough treatment of issues outstanding at the in-

TABLE 9
Evolution of Typical Hiroshima Survivor Dose Estimate: House Shielding at 1,500 m from Hypocenter

	Total neutrons	Total γ rays	Prompt Neutrons	Delayed neutrons	Prompt γ rays	Delayed γ rays	Shielding prompt neutron-γ rays	Shielding delayed neutron-γ rays	Body prompt neutron-γ rays	Body delayed neutron-γ rays
T57D										
Air dose	200	1000								
Shielded air dose	80	620								
T65DR										
Free-in-air kerma	101	216								
Shielded kerma	27	200								
Colon dose	3.8	75								
Marrow dose	7.7	104								
DS86										
Free-in-air kerma	8.43	488	8.25	0.17	221	267				
Shielded kerma	3.26	244	3.21	0.05	118	125	1.49	0.09		
Colon dose	0.51	173	0.51	0.00	87	83	1.08	0.06	1.37	0.06
Marrow dose	1.11	208	1.10	0.01	103	102	1.22	0.07	1.47	0.08
DS02										
Free-in-air kerma	8.97	525	8.54	0.44	213	312				
Shielded kerma	3.16	225	3.02	0.14	101	122	1.75	0.13		
Colon dose	0.43	160	0.41	0.01	76	81	1.24	0.09	1.59	0.11
Marrow dose	0.99	194	0.95	0.04	91	99	1.45	0.10	1.84	0.13

Notes. All doses are in mGy. The nine-parameter data for this hypothetical individual describe a single-story house wtth slant penetration of 5 m. The survivor was 7.5 m from a window in the direction of the hypocenter. The nearest structure providing frontal shielding was too far away (more than twice its height) to be considered in the original 9P coding but was accounted for in the updated coding used for DS02.

TABLE 10
Evolution of Typical Nagasaki Survivor Dose Estimate: House Shielding at 1,500 m from Hypocenter

	Total neutrons	Total γ rays	Prompt Neutrons	Delayed neutrons	Prompt γ rays	Delayed γ rays	Shielding prompt neutron-γ rays	Shielding delayed neutron-γ rays	Body prompt neutron-γ rays	Body delayed neutron-γ rays
						T57D				
Air dose	30	1000								
Shielded air dose	12	620								
						T65DR				
Free-in-air kerma	17	1191								
Shielded kerma	4.8	1101								
Colon dose	0.7	404								
Marrow dose	1.3	566								
						DS86				
Free-in-air kerma	6.32	898	6.06	0.26	482	416				
Shielded kerma	2.60	438	2.52	0.08	245	192	0.77	0.15		
Colon dose	0.47	308	0.46	0.01	178	128	0.55	0.11	0.79	0.10
Marrow dose	0.95	370	0.93	0.02	211	157	0.62	0.12	0.81	0.12
						DS02				
Free-in-air kerma	5.04	982	4.41	0.63	531	450				
Shielded kerma	1.85	390	1.65	0.21	222	167	0.60	0.17		
Colon dose	0.29	275	0.27	0.02	163	111	0.42	0.12	0.61	0.15
Marrow dose	0.63	332	0.57	0.06	195	135	0.49	0.14	0.67	0.18

Notes. All doses are in mGy. The nine-parameter data for this hypothetical individual describe a single-story house wtth slant penetration of 5 m. The survivor was 7.5 m from a window in the direction of the hypocenter. The nearest structure was too far away to be considered in the original 9P coding but was accounted for in the updated coding used for DS02.

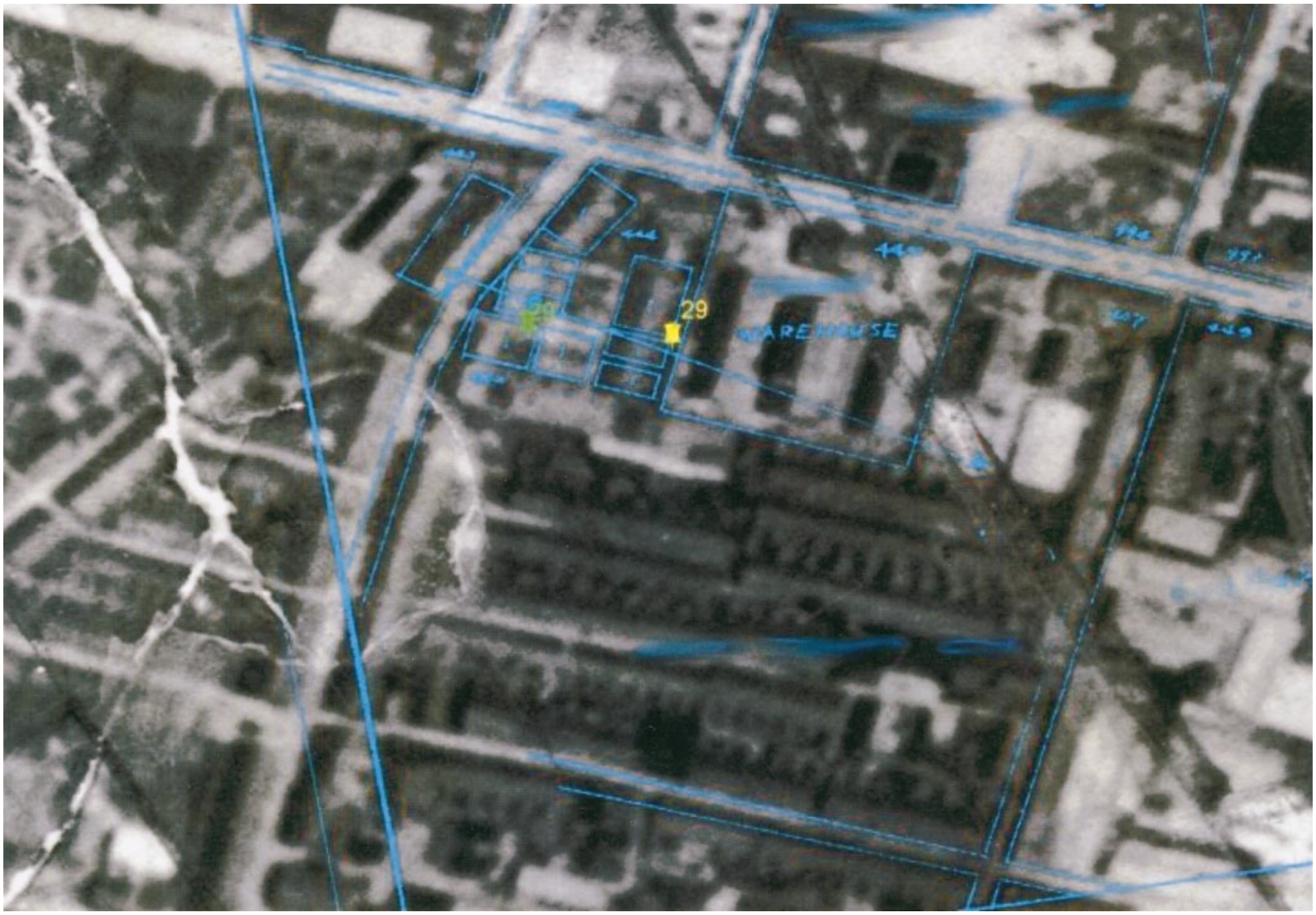

FIG. 11. Superposition of survivor shielding history neighborhood diagram (blue lines and text) on a pre-bombing aerial photograph aligned to the map. Although the map is not shown in this view, the aerial photographs could be very well aligned with the newer city maps with regard to many major streets and river channels. The green pushpin marker indicates the survivor position that was estimated on the aerial photograph as corresponding to that on the survivor shielding history neighborhood diagram and an accompanying house diagram. The survivor's position on the survivor shielding history neighborhood diagram is shown as a small blue circle just above the green pushpin. The arrow passing through that small blue circle indicates the direction to the hypocenter and the yellow pushpin marker indicates the location of the U.S. Army map coordinates originally assigned to the survivor. In this example, the location assigned to the survivor using the GIS would be about 25 m further from the hypocenter than the survivor's original U.S. Army map coordinates.

ception of the reassessment support the premise that DS02 is a sound system and that the fundamental issues affecting reliability have finally been resolved. The increased contribution of neutrons in Hiroshima that some observers expected from the ''neutron discrepancy'' did not emerge in DS02, and the actual organ doses due to neutrons in Hiroshima are a slightly smaller fraction of those due to γ rays in DS02 than in DS86, as suggested, for example, by Fig. 8. Interested readers can evaluate the average size of weighted neutron organ dose among survivors at a given distance, relative to γ-ray dose, by picking a value for colon or bone marrow from Fig. 7 and multiplying it by the reader's choice of weight. For example, in Hiroshima at 1,000 m with a chosen weight of 20 for neutrons, weighted neutron dose to colon is on average about 18% of γ-ray dose.

Although further development of the basic system by extramural working groups appears unlikely, some refinement can be foreseen, particularly at the level of implementation by RERF.

Work on the development dose error adjustment is continuing, with the development of methods that make fewer assumptions about the nature of the distribution of true doses and allow for the separation of errors as a result of grouping people into representative groups for dose computations and errors that arise as a result of imprecise or incomplete knowledge of the location and shielding of individual survivors or of the nature of the radiation produced by the bombs (*71*). It is likely that these new methods will eventually be used to provide updated DS02 survivor dose estimates, although preliminary indications are that this will make little difference in either individual survivor dose estimates or risk estimates based on the survivor doses.

It is also likely that efforts will be made to extract additional information about survivor location and shielding from survivor shielding history diagrams and similar materials. Modern Geographical Information System (GIS) software allows the ready and versatile alignment and superposition of maps, aerial photographs, drawings and similar archival sources of spatial information. Initial work suggests that this approach affords a substantial reduction in the error of survivor distance, at least for those with shielding histories, because the original map coordinates were assigned using relatively low-resolution and occasionally inaccurate war-era U.S. Army maps. Those maps are not of large enough scale to show the details of streets and other features, and the aerial photos and drawings traced from them could not be aligned and superimposed on the maps in the past. However, using more recent large-scale maps and modern GIS software, it is possible to accurately align shielding history drawings and aerial photographs with the map. Figure 11 illustrates superposition of a shielding history neighborhood drawing on a pre-bombing aerial photograph. When this photograph is aligned with the new Hiroshima city map, more accurate locations are specified.

Dose estimates for Nagasaki factory workers, who comprise a large portion of relatively high dose survivors in that city, remain problematic. Various biological indicators, including chromosome aberrations (*72*) and even solid cancer mortality (*73*), suggest that doses are likely to be overestimated for these survivors. Further efforts to understand and hopefully resolve this problem will continue.

The nature and quality of the atomic bomb survivor dosimetry have improved dramatically over the half-century since the survivor studies began. While individual DS02 dose estimates are not greatly different from DS86 estimates, the new system represents a significant improvement over its predecessors in that it is based on the latest understandings of the nature of the radiation produced by the Hiroshima and Nagasaki bombs, the underlying computations were carried out using more advanced and more detailed computer codes, an extensive body of high-quality physical measurements were used to validate the theoretical computations, and the basic system has been extended to address a number of shielding situations more carefully than in the past. RERF's implementation of DS02 provides documented dose estimates for the most comprehensive roster of study subjects ever assembled by RERF. The dose estimates, shielding data, and other relevant data are stored in a well-documented database that includes tools to facilitate easy, consistent access to dose estimates at appropriate levels of detail for both routine and specialized analyses. While continued efforts to improve both the dosimetry system as a whole and individual dose estimates are necessary and inevitable, we believe that DS02 dose estimates will provide a solid foundation for risk estimation and other RERF uses of atomic bomb survivor data for many years to come.

APPENDIX

TABLE A1
Regression Coefficients for DS02 Free-in-Air Kerma Components[a]

City	Component	Slant distance, *m*	α	β	γ
Hiroshima	Prompt neutrons	<1000	23.83	−0.00636	0.129
Hiroshima	Prompt neutrons	1000–2000	37.56	−0.00442	−2.14
Hiroshima	Prompt neutrons	2000+	32.97	−0.00462	−1.48
Hiroshima	Prompt γ rays	<1000	34.34	−0.00151	−1.91
Hiroshima	Prompt γ rays	1000–2000	29.05	−0.00205	−1.07
Hiroshima	Prompt γ rays	2000+	22.66	−0.00254	−0.0987
Hiroshima	Delayed neutrons	<1000	24.47	−0.00635	−0.332
Hiroshima	Delayed neutrons	1000–2000	29.54	−0.00590	−1.13
Hiroshima	Delayed neutrons	2000+	37.18	−0.00502	−2.37
Hiroshima	Delayed γ rays	<1000	26.23	−0.00306	−0.413
Hiroshima	Delayed γ rays	1000–2000	26.34	−0.00308	−0.425
Hiroshima	Delayed γ rays	2000+	36.78	−0.00233	−2.00
Nagasaki	Prompt neutrons	<1000	19.72	−0.00557	0.402
Nagasaki	Prompt neutrons	1000–2000	22.67	−0.00509	−0.0949
Nagasaki	Prompt neutrons	2000+	30.06	−0.00447	−1.23
Nagasaki	Prompt γ rays	<1000	24.52	−0.00278	−0.198
Nagasaki	Prompt γ rays	1000–2000	27.93	−0.00224	−0.770
Nagasaki	Prompt γ rays	2000+	51.46	−0.00071	−4.27
Nagasaki	Delayed neutrons	<1000	24.55	−0.00626	−0.355
Nagasaki	Delayed neutrons	1000–2000	31.09	−0.00549	−1.41
Nagasaki	Delayed neutrons	2000+	35.24	−0.00493	−2.11
Nagasaki	Delayed γ rays	<1000	26.74	−0.00304	−0.447
Nagasaki	Delayed γ rays	1000–2000	28.16	−0.00303	−0.655
Nagasaki	Delayed γ rays	2000+	24.02	−0.00329	−0.0427

[a] Because DS02 inherits the code from DS86, these coefficients calculate kerma in units of rad (cGy). Kerma on each indicated distance segment is calculated by the formula $K(SR) = e^{\alpha+\beta SR+(\gamma-2)\ln(SR)}$, where SR is the slant distance.

TABLE A2
Averaged Shielding Transmission Factors used in DS02

City	Shielding category	PN	PG	DN	DG	HPNG[a]	HDNG[a]
		Component					
Hiroshima	Average house	0.33	0.47	0.29	0.41	0.25	0.33
	Average outside	0.69	0.69	0.68	0.67	0.15	0.20
	Average any	0.42	0.53	0.39	0.48	0.22	0.30
Nagasaki	Average house	0.41	0.51	0.35	0.47	0.14	0.29
	Average outside	0.73	0.66	0.72	0.68	0.07	0.13
	Average any	0.49	0.55	0.45	0.52	0.12	0.25

[a] HPNG is the γ-ray component produced by interactions of prompt neutrons (PN) in the shielding, and the number given is not really a transmission factor, but rather the ratio of the HPNG component to the free-in-air *neutron* kerma at the same location. HDNG is the equivalent factor for delayed neutrons.

TABLE A3
Averaged Body Transmission Factors used in DS02 for Colon Dose

City	Age	PN	PG	DN	DG	HPNG	HDNG	BPNG[a]	BDNG[a]
Hiroshima	Adult	0.15	0.74	0.10	0.70	0.72	0.73	0.52	0.74
Hiroshima	Child	0.23	0.83	0.17	0.77	0.80	0.80	0.53	0.77
Hiroshima	Infant	0.31	0.85	0.25	0.81	0.84	0.84	0.51	0.75
Nagasaki	Adult	0.19	0.75	0.11	0.70	0.72	0.72	0.31	0.61
Nagasaki	Child	0.27	0.82	0.18	0.78	0.79	0.79	0.32	0.66
Nagasaki	Infant	0.36	0.84	0.26	0.81	0.84	0.84	0.29	0.63

[a] BPNG is the γ-ray component produced by interactions of prompt neutrons in the body, and the number given is not really a transmission factor, but rather the ratio of the BPNG component to the *shielded neutron* kerma at the same location. BDNG is the equivalent factor for delayed neutrons.

TABLE A4
Averaged Body Transmission Factors used in DS02 for Bone Marrow Dose

City	Age	PN	PG	DN	DG	HPNG	HDNG	BPNG[a]	BDNG[a]
Hiroshima	Adult	0.30	0.85	0.26	0.77	0.82	0.82	0.55	0.80
Hiroshima	Child	0.42	0.92	0.37	0.85	0.88	0.88	0.49	0.72
Hiroshima	Infant	0.53	0.94	0.48	0.89	0.93	0.93	0.43	0.65
Nagasaki	Adult	0.34	0.85	0.27	0.77	0.81	0.82	0.32	0.66
Nagasaki	Child	0.46	0.91	0.38	0.84	0.87	0.88	0.29	0.62
Nagasaki	Infant	0.56	0.93	0.49	0.89	0.92	0.92	0.25	0.54

[a] BPNG is the γ-ray component produced by interactions of prompt neutrons in the body, and the number given is not really a transmission factor, but rather the ratio of the BPNG component to the *shielded neutron* kerma at the same location. BDNG is the equivalent factor for delayed neutrons.

ACKNOWLEDGMENTS

The Radiation Effects Research Foundation (RERF), Hiroshima and Nagasaki, Japan is a private, non-profit foundation funded by the Japanese Ministry of Health, Labour, and Welfare and the U.S. Department of Energy, the latter through the National Academy of Sciences. The existence of a credible and comprehensive dosimetry system for use in the atomic bomb survivor studies is the result of the efforts of hundreds of people over many decades. Those deserving special mention for their contributions during the earlier years of the dosimetry studies at RERF/ABCC include Ed Arakawa, John Auxier, Joe Cheka, Tadashi Hashizume, Harry Hubbell, Jr., Sam Hurst, Seymour Jablon, Troyce Jones, Takashi Maruyama, Roy Milton, Ken Noble, Yoshio Okamoto, Rufus Ritchie, Takao Shohoji, Hiroaki Yamada, and, more recently, Tadaaki Watanabe and Tomoaki Yamashita. Contributions to the dosimetry studies by others are well documented in the DS86 Report (available on the RERF website at http://www.rerf.jp/shared/ds86/ds86a.html) and DS02 Report (will be made available on the RERF website). We are particularly indebted to Stephen D. Egbert of Science Applications International Corporation, San Diego, CA, for valuable discussions concerning the energy distributions of DS02 fluences. This paper is dedicated to Dr. Shoichiro Fujita, a devoted participant in the atomic bomb dosimetry work as a researcher for almost four decades at ABCC and RERF. His untimely death from cancer during the final preparation of this paper, on April 3, 2005, took from us a loyal and cherished friend and colleague.

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